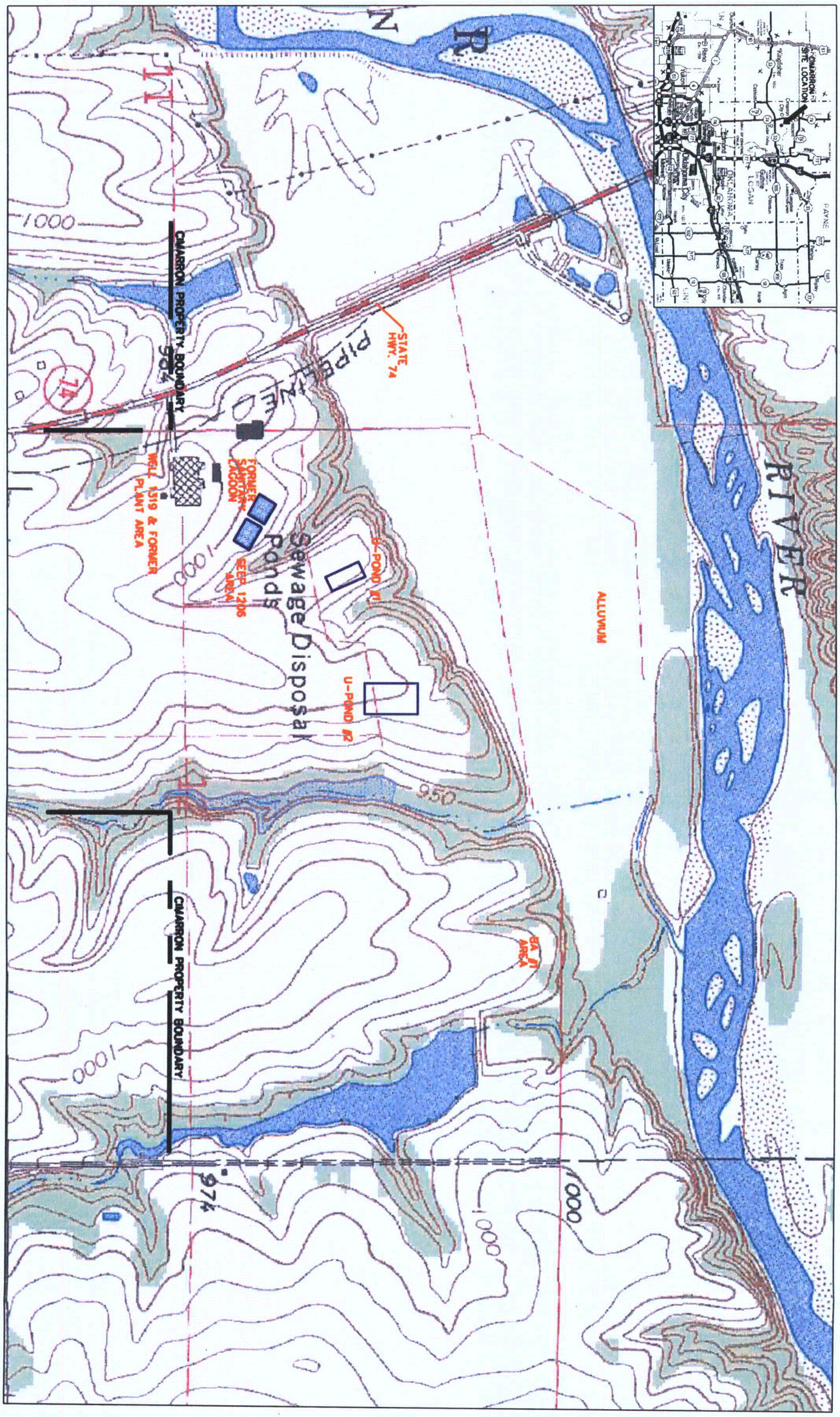
Figures

DWG. NO. 040200056



REFERENCE: UNITED STATES GEOLOGICAL SURVEY
CRESCENT QUADRANGLE, OKLAHOMA-LOGAN CO.
7.5 MINUTE SERIES (TOPOGRAPHIC), 1970 (PHOTOINSPECTED 1981).

0 800 1600
SCALE IN FEET

FIGURE NUMBER:	SHEET NUMBER:
1	1

FIGURE 1
SITE LOCATION MAP
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1" = 800'	9/22/06	04020-044-327

ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

DESIGNED BY:	
DRAWN BY:	JAS
CHECKED BY:	DJF
APPROVED BY:	DJF

REVISIONS

NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS
3.		6/8/05	JAS

DWG. NO. 040200012

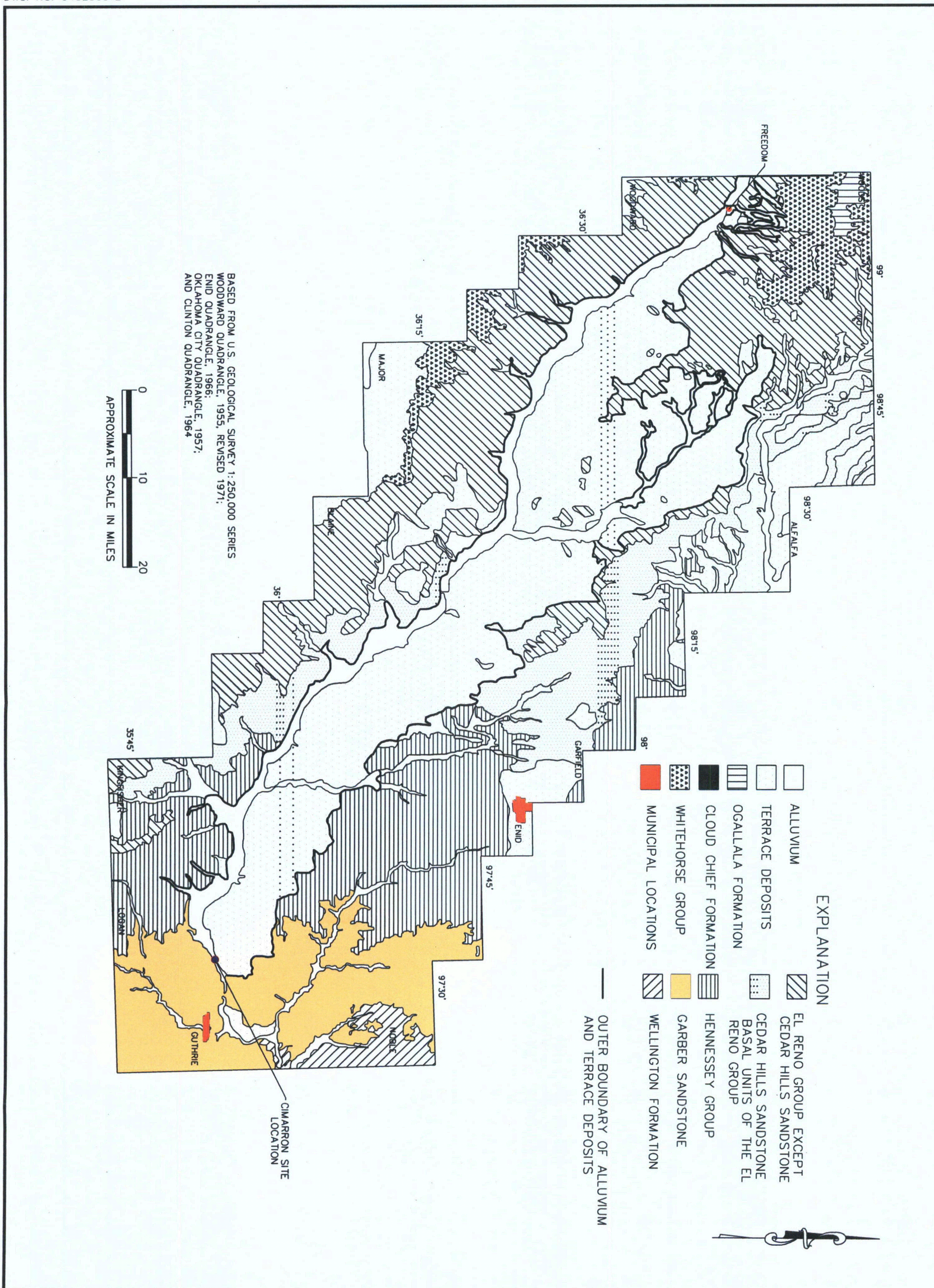


FIGURE NUMBER:	SHEET NUMBER:
2	1

FIGURE 2
GEOLOGY ALONG THE CIMARRON RIVER
FROM FREEDOM TO GUTHRIE, OKLAHOMA
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1"=10 miles	9/22/06	04020-044-327

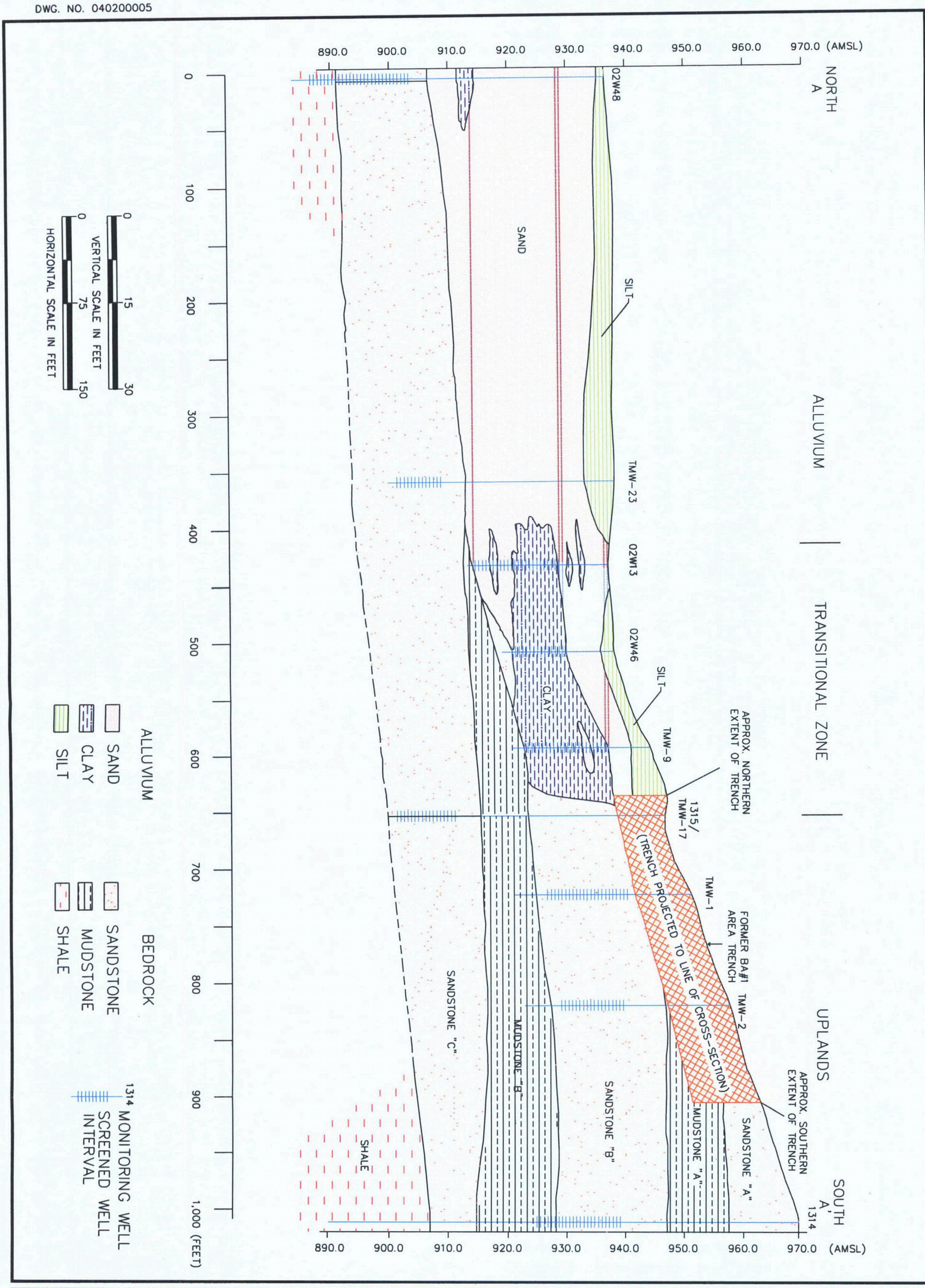
ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

DESIGNED BY:
DRAWN BY: JAS
CHECKED BY: DJF
APPROVED BY: DJF

REVISIONS			
NO.:	DESCRIPTION:	DATE:	BY:
1.		4/10/05	JAS
2.		6/17/05	JAS

DWG. NO. 040200005



SHEET NUMBER:	FIGURE NUMBER:
1	3

FIGURE 3
BA #1 AREA
REPRESENTATIVE GEOLOGICAL CROSS-SECTION
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1" = 75'	9/22/06	04020-044-327

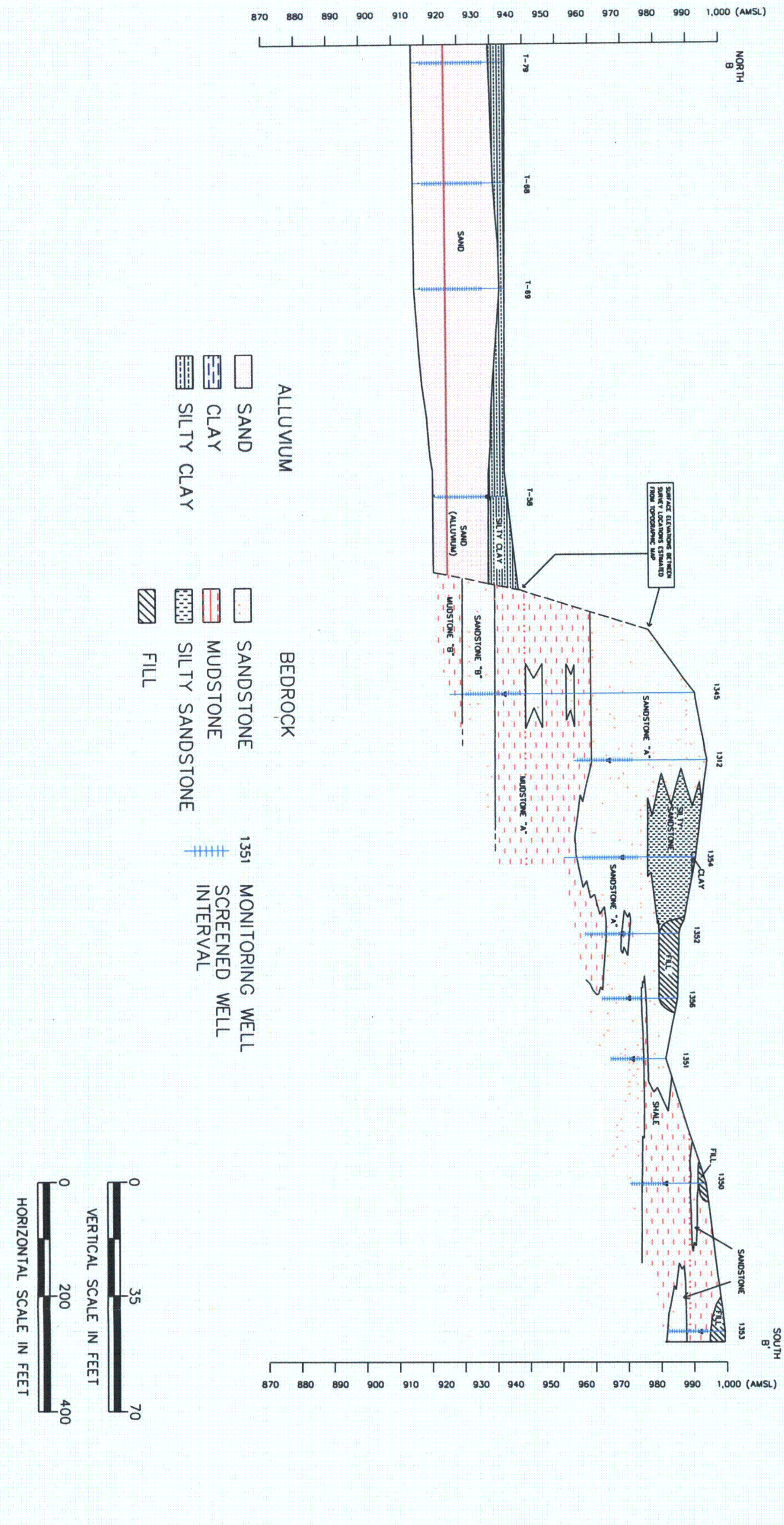
ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

DESIGNED BY:	
DRAWN BY:	JAS
CHECKED BY:	DJF
APPROVED BY:	DJF

NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS

DWG. NO. 040200009



SHEET NUMBER:	FIGURE NUMBER:
1	4

FIGURE 4
REPRESENTATIVE GEOLOGICAL CROSS-SECTION
WESTERN UPLAND AND ALLUVIAL AREAS
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1" = 200'	9/22/06	04020-044-327

ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

DESIGNED BY:	REVISIONS			
	NO.:	DESCRIPTION:	DATE:	BY:
DRAWN BY:	1.		4/01/05	JAS
JAS	2.		6/17/05	JAS
CHECKED BY:				
DJF				
APPROVED BY:				
DJF				

N

BA #1 Boundary

NOT TO SCALE

BA #1 Model Domain
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

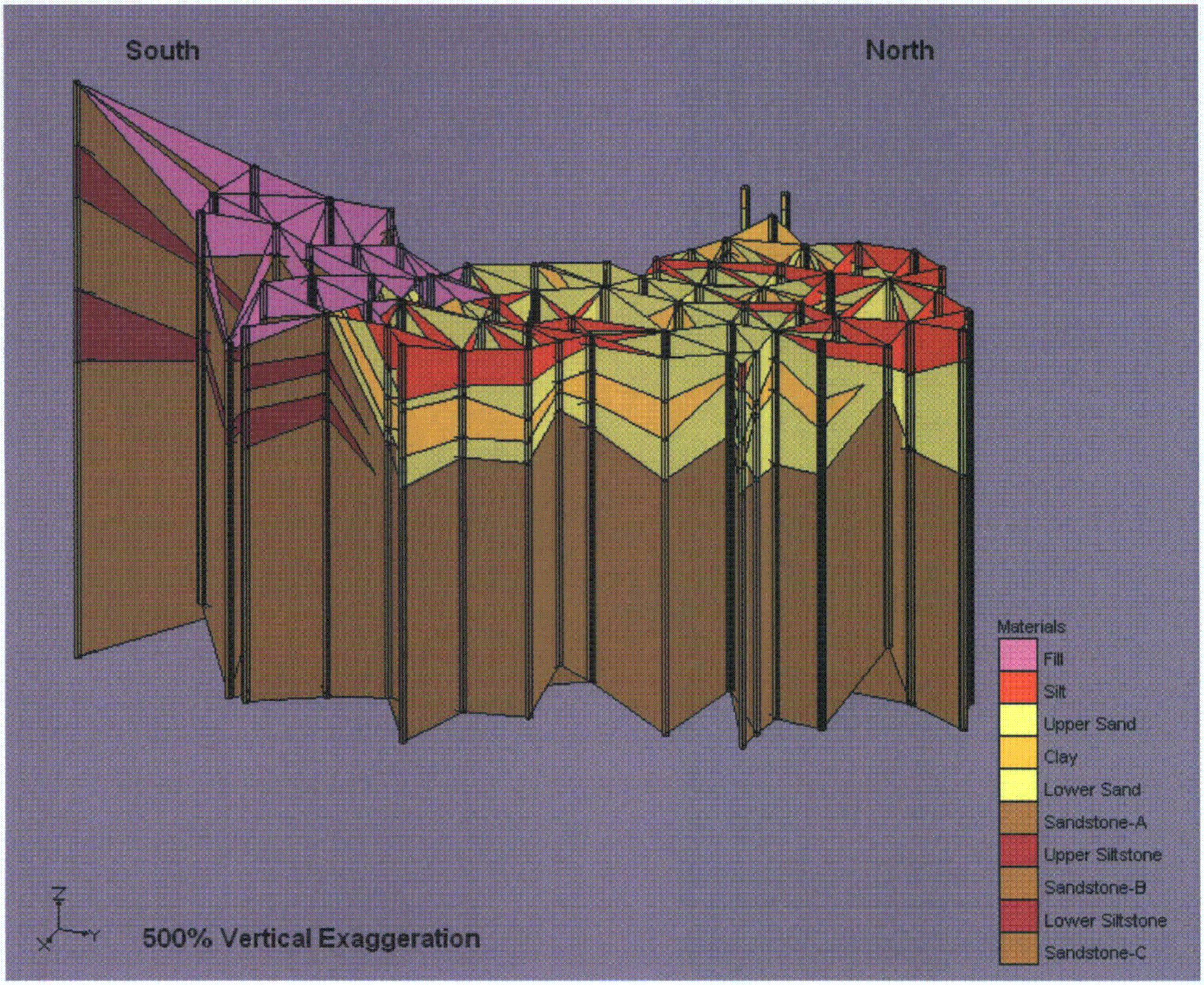
DATE	PROJECT
October 2006	04020-044-300

Figure
5

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure5.mxd

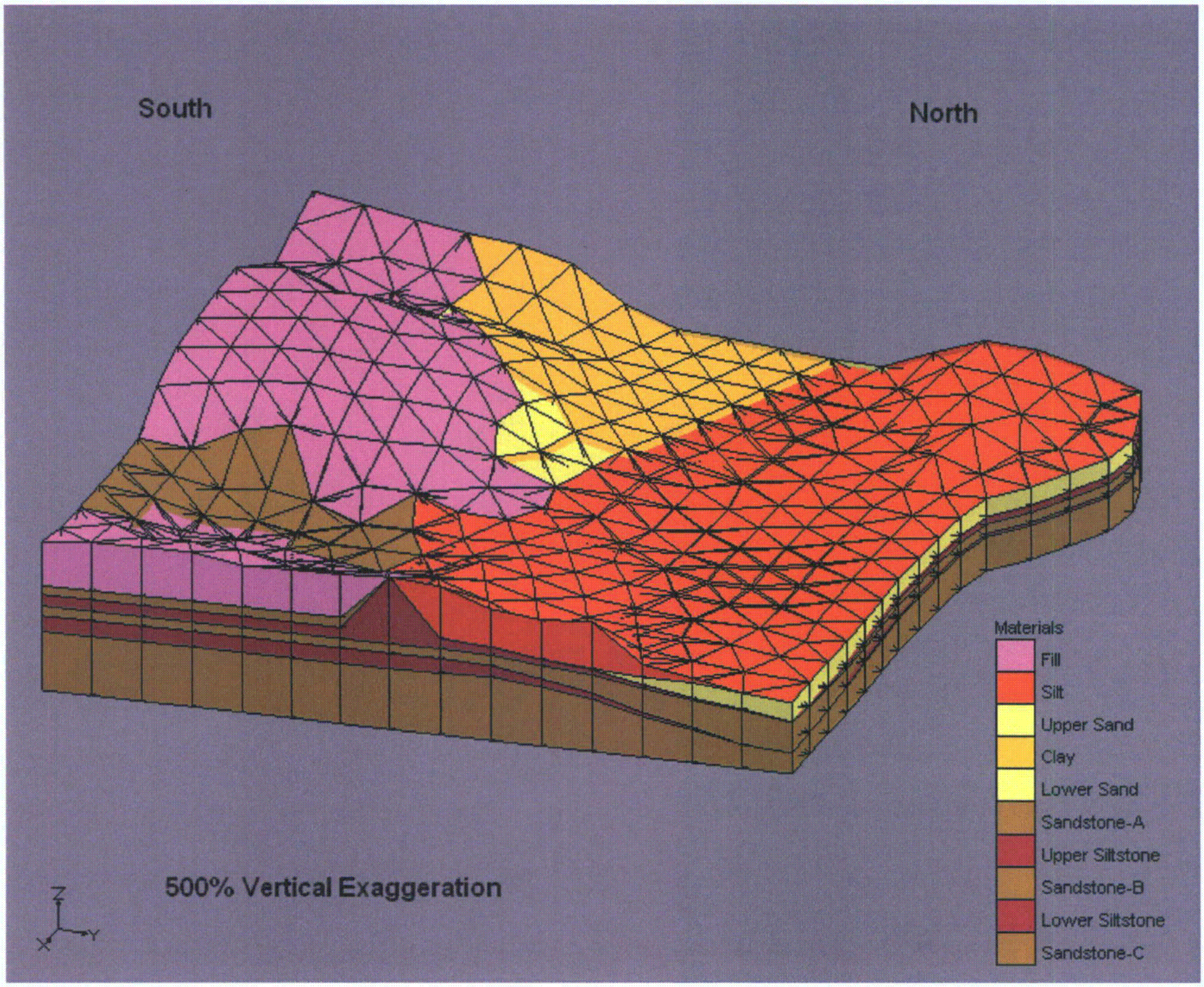
N — WA Area Boundary NOT TO SCALE	WA Area Model Domain Cimarron Corporation Crescent, Oklahoma	ENSR | AECOM
	DATE: October 2006 — PROJECT: 04020-044-300	Figure 6

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\FI0BD2~1.MXD



BA #1 Boreholes and Cross-sections Cimarron Corporation Crescent, Oklahoma		ENSR | AECOM
DATE	PROJECT	Figure 7
October 2006	04020-044-300	

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure7.mxd



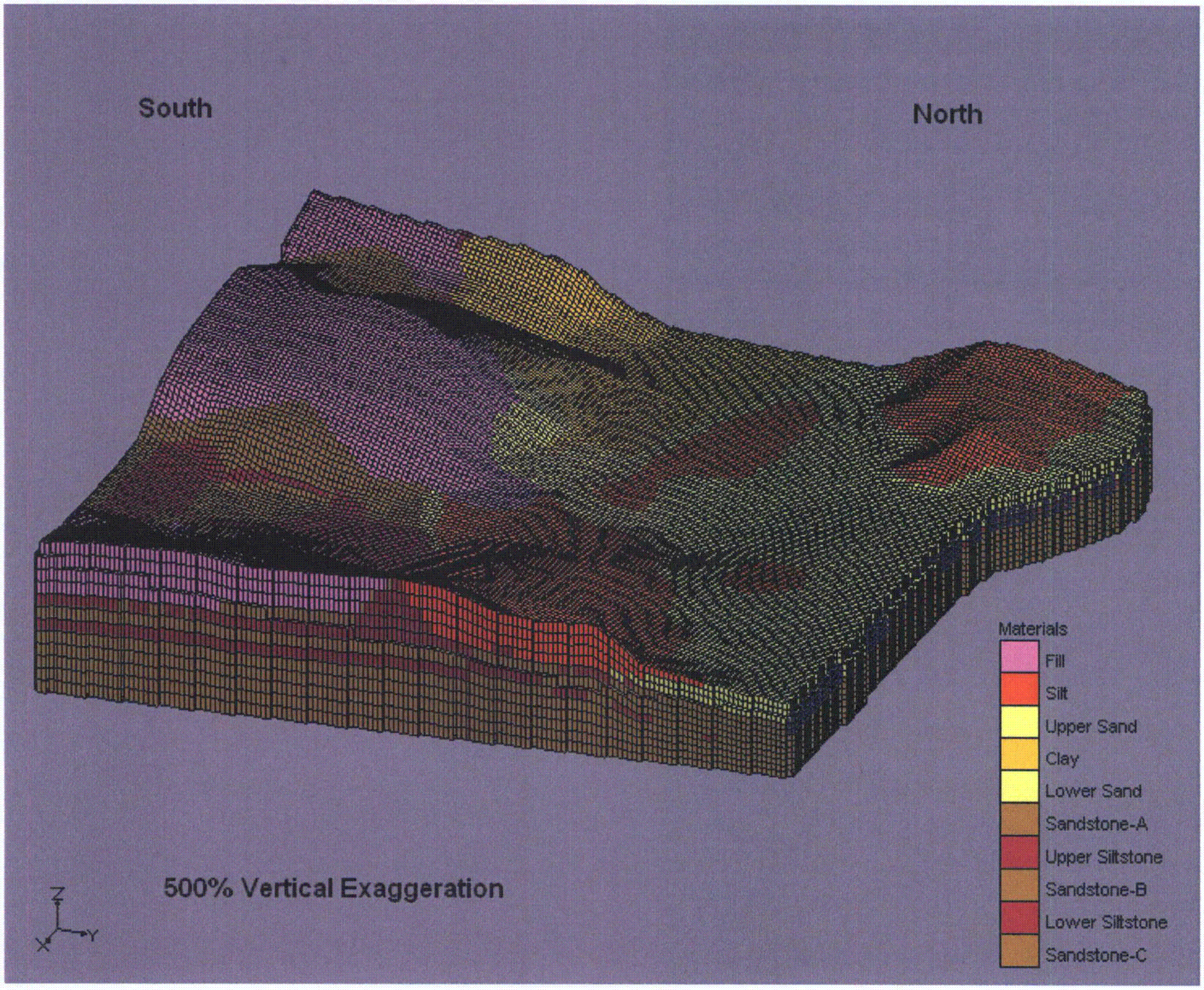
BA #1 Solids Developed
from Borehole Data
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

Figure
8

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure8.mxd



BA #1 3D Grid Incorporating
Geologic Information
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

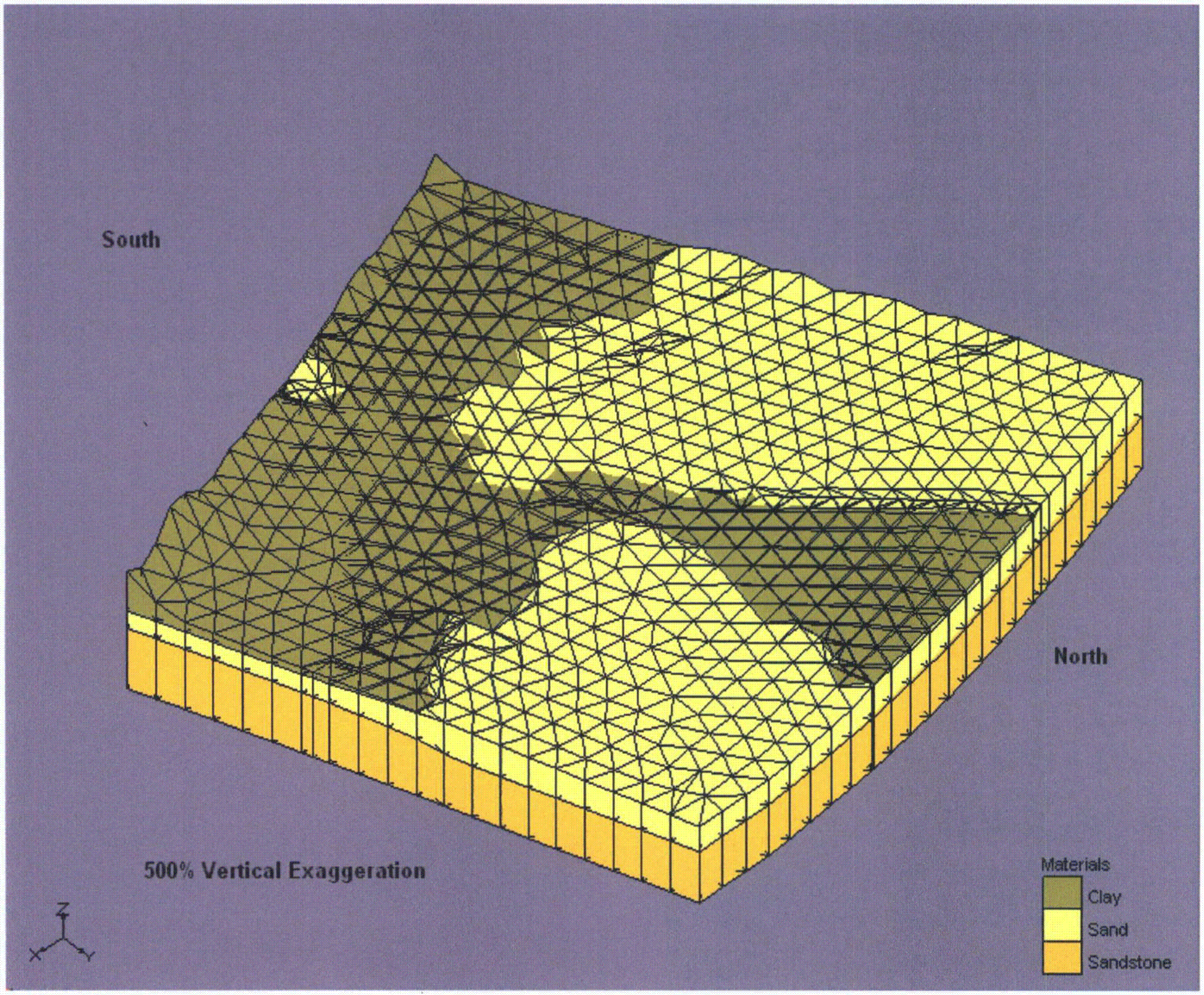
Figure
9

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure9.mxd

Note:
Shows extent of borings
and cross-sections.
Figure 11 shows extrapolation
of geology to model domain.

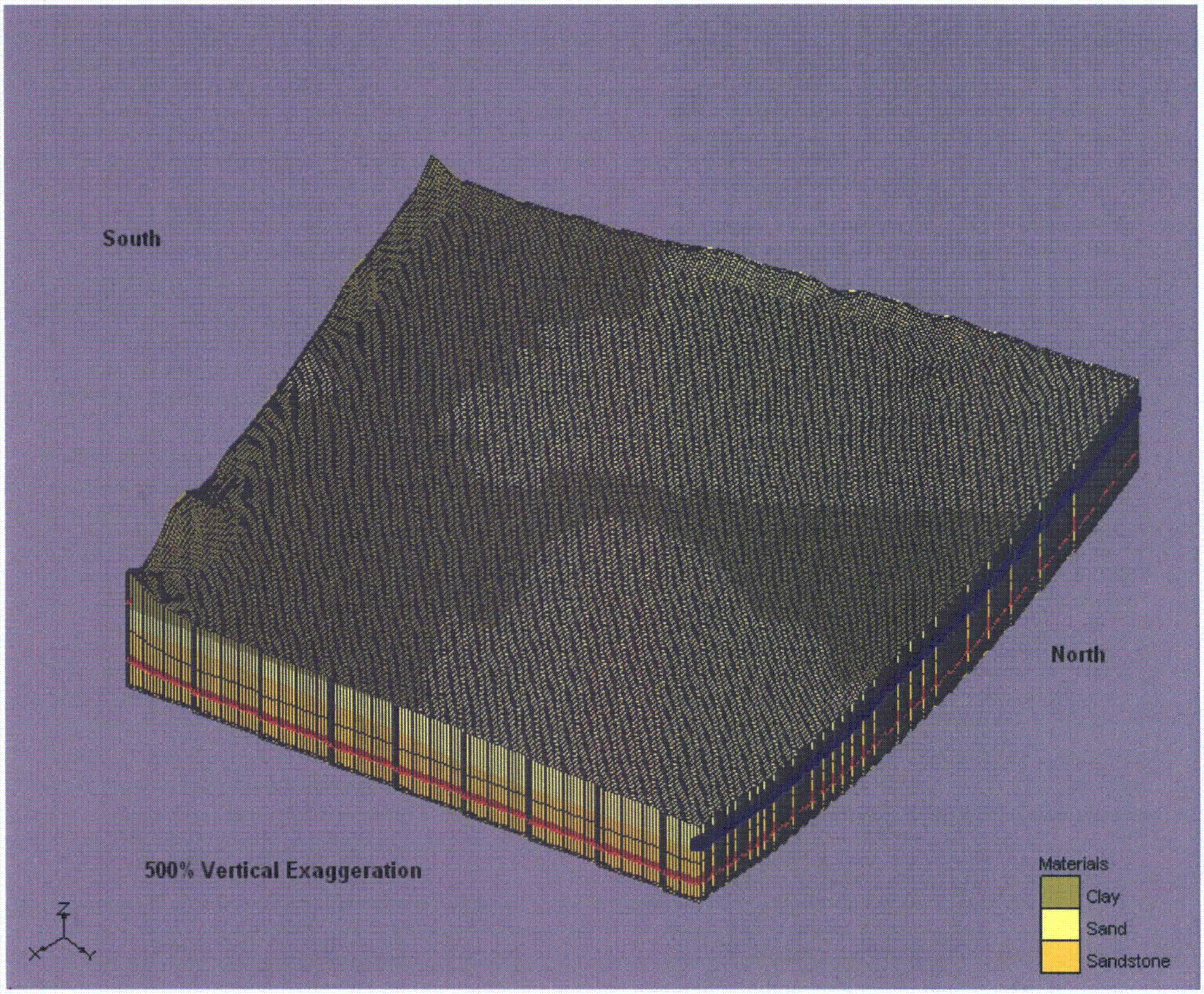
	WA Area Boreholes and Cross-sections Cimarron Corporation Crescent, Oklahoma	ENSR | AECOM
	DATE: October 2006 — PROJECT: 04020-044-300	Figure 10

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure10.mxd



WA Area Solids Developed from Borehole Data Cimarron Corporation Crescent, Oklahoma		ENSR AECOM
DATE	PROJECT	Figure 11
October 2006	04020-044-300	

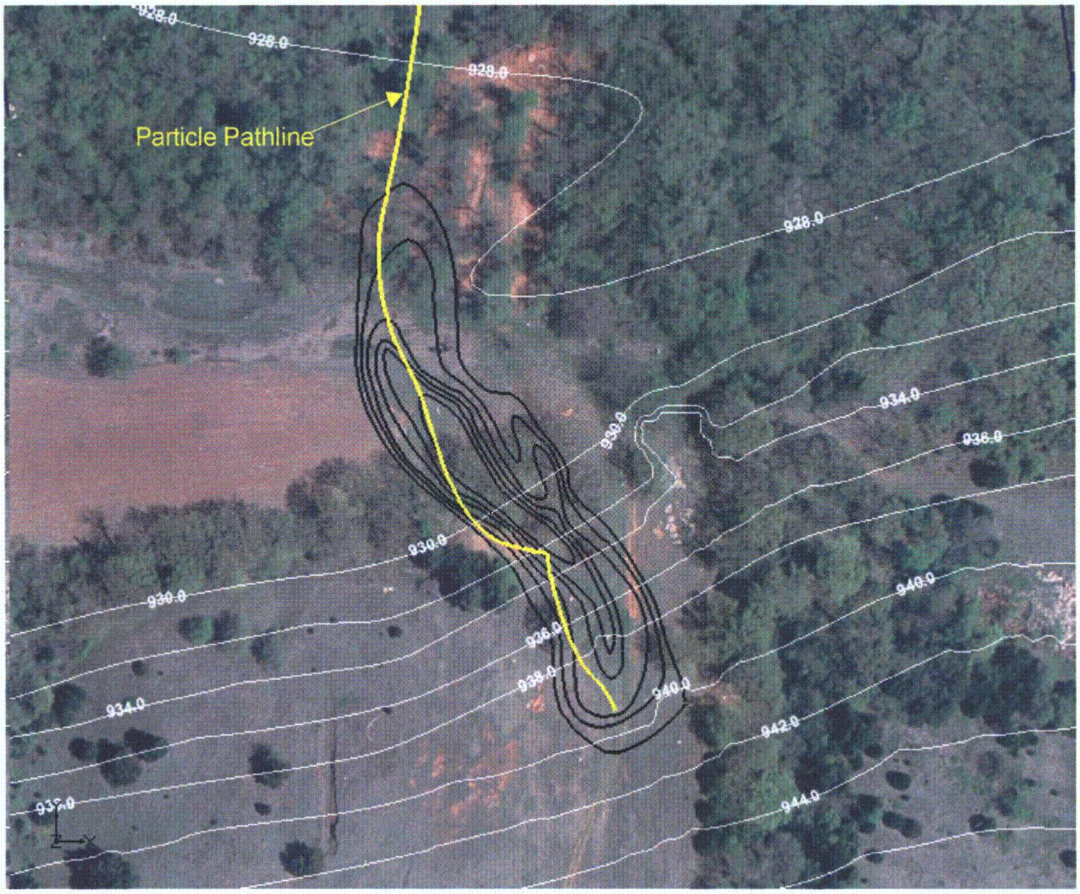
J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure11.mxd



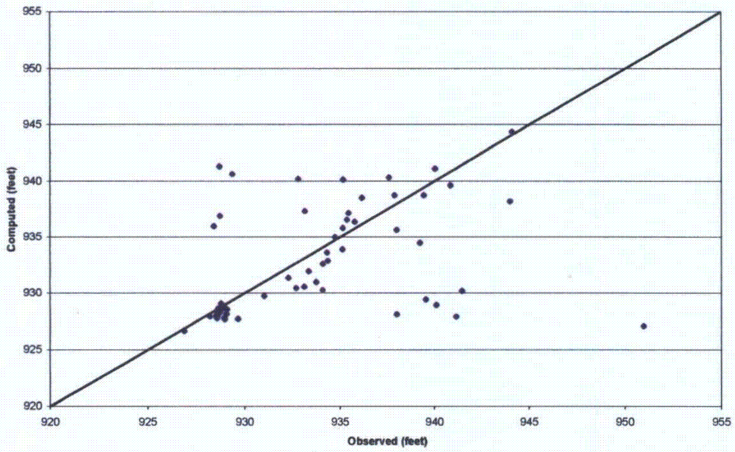
	WA Area 3D Grid Incorporating Geologic Information Cimarron Corporation Crescent, Oklahoma		ENSR | AECOM
	DATE	PROJECT	Figure 12
	October 2006	04020-044-300	

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure12.mxd

Predicted Groundwater Contours and Particle Pathlines



MODFLOW Computed vs Observed Groundwater Levels



N

NOT TO SCALE

Results of Burial Area #1 Model Calibration: Predicted Groundwater Contours with Pathline and Measured vs Predicted Water Levels

October 2006

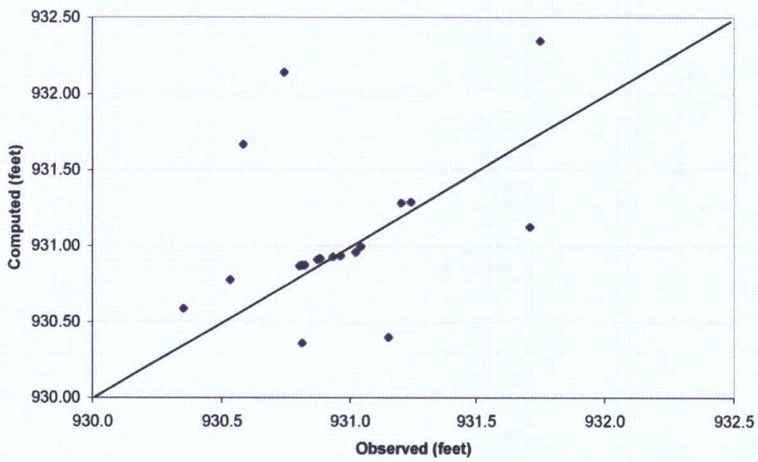
ENSR | AECOM

Figure
13

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\FIFF2A~1.MXD

Predicted Groundwater Contours

MODFLOW Computed vs Observed Groundwater Levels



N

NOT TO SCALE

Results of Western Alluvial Area Model Calibration: Predicted Groundwater Contours and Measured vs Predicted Water Levels

October 2006

ENSR | AECOM

Figure
14

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure14.mxd

Appendix B

Hydrology Addendum (ENSR)

ENSR

Prepared for:
Cimarron Corporation
Crescent, Oklahoma

Hydrology Addendum
Cimarron Site, Crescent, Oklahoma
Final

ENSR Corporation
April 2008
Document No.: 04020-044-400

Contents

List of Tables

List of Figures

1.0 Introduction

In December 2006 Cimarron Corporation (Cimarron) submitted a License Amendment Request (LAR) to the NRC for the purposes of amending the Cimarron Site Decommissioning Plan (SDP) and addressing specific changes to the Cimarron license conditions. The SDP portion of the LAR included the following documents:

- Work Plan for In-Situ Bioremediation of Groundwater at the Cimarron Site (ARCADIS, 2006); and;
- Groundwater Flow Modeling Report (ENSR, 2006b).

In March of 2007, having reviewed the submittal, the NRC identified 17 deficiencies related to these submittals. Several of the deficiencies related to transient hydrologic processes which may impact a remediation design.

In response, ENSR has prepared this Hydrology Addendum, which provides a characterization of site hydrology. Based on this characterization, ENSR evaluated the impacts transient hydrologic events have on the water budget in the variably-saturated zone and, specifically on recharge to groundwater. Accordingly, ENSR considered the following hydrologic transient events: 1) periods of heavy rainfall; 2) river flood stage events; and 3) ponded water vertically infiltrating to the water table.

Terminology such as vadose zone, capillary zone, etc. may be used in the Work Plan and/or other documents; these have specific meanings in the context they are used. **Note that for the purposes of this document the variably-saturated zone is defined as the soil horizon that extends from the ground surface to the average groundwater level.** Among other topics, this report deals with the water budget in this zone.

1.1 Background & Overview

Cimarron's site near Crescent, Oklahoma, is a former nuclear fuel manufacturing facility. Since the cessation of operations, the site has been undergoing decommissioning. This decommissioning is being performed by Cimarron Corporation with oversight from the Nuclear Regulatory Commission (NRC) and the Oklahoma Department of Environmental Quality (Oklahoma DEQ).

The Conceptual Site Model (CSM Rev 01) prepared by ENSR and finalized in October 2006 updated the understanding of Cimarron Site's geology and hydrogeology based on site data. The CSM Rev 01 focused specifically on three areas where impacts have yet to be fully remediated: Burial Area #1 (BA #1 Area); the Western Upland Area; and the Western Alluvial Area. CSM Rev 01 (ENSR, 2006a) included information such as:

- Regional, site, and area specific stratigraphy;
- Regional, site, and area specific groundwater flow patterns (i.e., directions, gradients, sources and sinks of groundwater); and
- Regional, site, and area specific groundwater chemistry.

These three components were integrated into a conceptual model that describes the fate and transport processes that control impact to receptors in each of the three areas at Cimarron. Conclusions and recommendations identified that each of the three areas had been sufficiently characterized such that a remediation design could be completed.

One key assumption of the CSM Rev 01 was that the site could be confidently evaluated based on steady state conditions. That is, transient conditions such as changes in river stage and/or isolated precipitation events are short in duration. It was stated in the CSM Rev 01 report that these events may result in short term changes in groundwater velocities and directions, but that because they are short-term, their impacts are negligible relative to the long-term average groundwater conditions. Early remediation designs were based on the assumption that remediation would be required for a time frame consistent with long-term average groundwater conditions (i.e., greater than a few years). Thus, evaluating the site on a steady-state basis was considered acceptable.

However, the NRC expressed concern in their letter of deficiencies (March 2007) that in fact the transient hydrologic processes (changes in river stage and/or precipitation events) may have short-term impacts to groundwater and geochemical conditions during and after remediation is completed. Specifically the NRC expressed concern about the potential impact of water infiltration on sorbed uranium migrating to the water table. This infiltration could be caused by precipitation or flooding. The NRC also noted that the recharge water, which may have different geochemical characteristics from groundwater below, may impact groundwater quality. According to the NRC, these potential impacts needed to be accounted for in the development of a remediation design.

1.2 Objectives & Approach

To address the NRC's concerns, ENSR has prepared this hydrology addendum to evaluate the impacts transient hydrologic processes have on the water budget in the variably-saturated zone and specifically on recharge to groundwater. This document focuses on quantifying the water budget, although some conclusions are drawn regarding water quality based on the findings herein. In-depth discussions of water quality are addressed in the Site Decommissioning Plan – Groundwater Decommissioning Plan (ARCADIS, March 2008), submitted as part of the revised LAR along with this Addendum.

The specific objective of this Addendum is to characterize the impacts precipitation and surface water hydrology may have on variably-saturated soils and recharge to groundwater. The findings can be used, as necessary, to help develop a comprehensive remediation design.

To achieve this objective the following steps will be completed:

- Characterize regional climate;
- Characterize typical and extreme rainfall events;
- Characterize typical and extreme Cimarron River conditions; and
- Evaluate water budget in the variably-saturated zone soils during normal and extreme circumstances.

Starting in April 2007, the Cimarron Site experienced several months of high precipitation and river flows. This report includes overviews of the river and groundwater responses to the precipitation data collected over the spring and summer of 2007. These recent precipitation events were divided into four periods: late March/early April 2007, early May 2007, mid-June/late July 2007, and mid-August 2007; each of these periods are discussed individually.

Modeling was completed using the Hydrologic Evaluation of Landfill Performance (HELP) model to estimate recharge volumes to the variably-saturated zone and the water table. A summary of that modeling follows the discussion of the recent hydrologic events. The discussion of the background and set-up of the model is described as well as base case model runs. Several scenarios were then simulated to address: 1) extreme precipitation events and 2) ponding events.

A summary and conclusions section appears at the end of this document in which key points are highlighted both from the evaluation of the recent-past hydrologic events and the modeling conducted.

2.0 Site Setting

The Cimarron Site lies within the Osage Plains of the Central Lowlands section of the Great Plains physiographic province, just south of the Cimarron River in Logan County, Oklahoma. The Cimarron Site is located approximately 30 miles north of Oklahoma City, OK. The site boundaries extend approximately one mile south from the south bank of the Cimarron River and approximately one mile east from Route 74 on the west (**Figure 2-1**).

2.1 Regional Climate

The Oklahoma Climatological Survey (OCS) collects and maintains a database of climatic conditions across Oklahoma and in Logan County. Oklahoma is located in the nearly flat to rolling Southern Great Plains. Within the plains are hillier areas, which contain as much as 600 feet of relief between higher hills and lower valleys. These hillier areas tend to be at the edges of the State: the Wichita Mountains in the southwest, the south central Arbuckle Mountains, the Ouachita Mountains in the southeast, the Ozark Plateau in the northeast, and the Black Mesa in the panhandle. The Red River and the Arkansas River are within the Mississippi River Basin and are the two major rivers in the State that both discharge directly to the Mississippi River.

Overall the climate of Oklahoma is strongly influenced by conditions that develop in the Gulf of Mexico. Summers tend to be long and hot compared to the northern Plains States; winters are shorter and milder. Annual average relative humidity ranges from 60% to 70%. Evapotranspiration and percolation are at least 80% of Oklahoma's precipitation; runoff and storage therefore account for the remaining 20%.

Average temperatures in the State range from 58°F to 62°F, with averages generally higher eastward. High temperatures (over 90°F) typically occur from 60 to 115 days per year, again depending on location. Temperatures exceeding 100°F occur frequently, generally between May and September. The hottest temperature on record, 120°F, occurred several times at several locations over the last 7 decades. Temperatures below 32°F occur 60 to 110 days per year, depending on location and elevation. The lowest temperature, -27°F, has occurred twice in 1905 and 1930. The growing season ranges from 175 to 225 days depending on location and elevation.

The spatial distribution of rainfall across the State is characterized by a sharp decrease in rainfall from east to west. In the far southeast, average annual rainfall is estimated at approximately 56 inches per year while the average annual rainfall in the far western panhandle may be as low as 17 inches per year. Rainfall typically falls in late spring, mainly May, except in the far west (panhandle). In much of the State, a second peak in rainfall occurs in September. In the western panhandle, the double peak pattern is not observed; most rainfall occurs in the June-July timeframe. Wintertime precipitation events tend to be a result of regional weather systems, while summertime precipitation results from mesoscale convective storms and other thunderstorms. Rainfall amounts up to 20 inches per day have also been reported, but these numbers are unofficial (i.e., non-standard).

The greatest snowfalls tend to be in the northwestern portion of the State where several events can occur in one year. In contrast, it can be several years between snowfall events in the southeast. The effects of snowfall in Oklahoma are generally short-lived; that is, snow melts within a few days of the event. Ice storms are possible, but ice accumulation is typically less than an inch.

Flooding along rivers and tributaries results from precipitation and for that reason occurs during the months of the highest precipitation. Impacts from droughts are linked to the duration of the drought. In the last century (approximately) there have been five multi-year drought events lasting six to ten years.

2.2 Local Climate

The Oklahoma Climatological Survey (OCS) collects and maintains a database of climatic conditions that have been used to characterize the climate across Logan County. Average annual precipitation ranges from 33 to 39 inches per year across the county. Temperatures average near 61°F with a typical yearly range of 95°F in the late summer to 26°F in January. Severe climatological events include periodic thunderstorms and tornadoes; 41 tornadoes have been documented in Logan County in the last 53 years. In depth summary statistics of climatological factors have been prepared by the OCS and can be found on line at http://climate.ocs.ou.edu/county_climate/Products/CountyPages/logan.html.

2.3 Geology & Soils

An in-depth description of the geologic setting of the Cimarron Site is included in the CSM Rev. 01 (ENSR, 2006a). In summary, the regional geology of the Cimarron area consists of Permian-age sandstones and mudstones of the Garber-Wellington Formation of central Oklahoma overlain by soil in the upland areas and Quaternary alluvial sediments in the floodplains and valleys of incised streams. The Garber Formation at the project site is a fluvial deltaic sedimentary sequence consisting of channel sandstones and overbank mudstones. The channel sandstones are generally fine-grained, exhibit cross-stratification, and locally have conglomeratic zones of up to a few feet thick. The sandstones are weakly cemented with calcite, iron oxides, and hydroxides. The silt content of the sandstones is variable and clays within the fine fraction are generally kaolinite or montmorillonite. The mudstones are clay-rich and exhibit desiccation cracks and oxidation typical of overbank deposits. Some of the mudstones are continuous enough at the Cimarron Site to allow for separation of the sandstones into three main units, designated (from top to bottom) as Sandstones A, B, and C. Within each sandstone unit, there are frequent mudstone layers that are discontinuous and not correlative across the project area.

The soil distribution between the uplands and low lands differs considerably. The distribution of soil types is important for understanding the spatial variability in recharge and runoff. The Natural Resources Conservation Services (NRCS) provides an online soil mapping tool which was used for the following discussion (http://websoilsurvey.nrcs.usda.gov/app/). Lowland or floodplain soils tend to be in the Yahola Class while upland soils tend to be Ironmound-Coyle type soils. This is consistent with the origins of the soils. The flood plain soils may originate from both upland erosion and flood event deposition. The upland soils more likely originate from the local parent rock – mudstones and sandstones.

Specifically, the floodplain soils are characterized as follows:

- Soils are typically loams and sandy loams with smaller percentages of clay, resulting in high permeabilities consistent with the underlying alluvial materials.
- Slopes are around 10% or less.
- Because of the higher permeabilities and low slopes, recharge is expected to be higher and runoff lower than in the uplands.

In contrast, the upland soils (Burial Area #1 and Western Upland area) are characterized as follows:

- Soils generally contain a higher percentage of silts, clays, and fine sands, resulting in overall lower permeabilities, consistent with the parent rock, sandstones.
- Slopes tend to be steeper than in the floodplain, up to 45% grade.
- The lower permeabilities coupled with the steeper slopes yield lower recharge and higher runoff than that associated with the floodplain soils.

In general, based on NRCS descriptions of hydraulic conductivity, the permeability of the soils in the flood plain are greater than those in the uplands. It is estimated that floodplain soils have hydraulic conductivities in the range of tens of feet per day. The exception to this is where clays are present where conductivities may be one to two orders of magnitude less than the other floodplain soils. NRCS data indicates that conductivities of floodplain soils tend to increase with depth. In contrast, the upland soils tend to be in the ones of feet per day and conductivities decrease with depth, suggesting increased competency and decreased permeability of the sandstone units. The implications of these varying soil types impact the simulations of vertical infiltration. Sandier or loamier soils will tend to percolate water better than silty or clayey soils. Silty and clayey soils may percolate water so slowly that water will pond; i.e. infiltration is limited by the vertical transmissivity properties of the soils.

3.0 Site Hydrology

3.1 Water Budget

The purpose of this section is to summarize the components of the water budget, specifically how precipitation is expected to be partitioned among recharge, evapotranspiration (ET), and runoff. This discussion will provide a context for understanding the site and will form the basis for comparing expected site behavior to model results (Section 4.0).

The following table summarizes the values and ranges of each of these components based on literature review. The extreme-event precipitation depths have been included because they are important in understanding the extreme event recharge, which provides one basis for evaluating a remediation design.

	Value/Range	Source
Precipitation	24 inches/year near Freedom, OK (100 mi NW of Site)	Adams & Bergmann, 1995
	32-42 inches/year at Guthrie, OK	
	33-39 inches/year	Oklahoma Climatological Survey (OCS)
	35.93 inches/year average	
	2.65 inches; 24-hour, 2-year event	USGS, 2007b
	6.2 inches; 24-hour, 100-year	
	3.3 inches; 24-hour, 2-year event	Rea and Tortorelli, 1999
	9.5 inches; 24-hour, 100-year	
Recharge to the groundwater	8% of precipitation	Adams & Bergmann, 1995
	6.6-26% of precipitation	Reed, et. al., 1995
	2.5% of precipitation	Belden, 2000
	8% of precipitation	ENSR, 2006b
Evapotranspiration (ET)	Approaching equal to precipitation	Geraghty, et al., 1973
Runoff	7% of precipitation, 2-3 inches/year	Belden, 2000
	1-5 inches/year	Geraghty, et al., 1973

- Recharge is defined as that water that percolates into the soils and moves past the root zone, avoiding root uptake, ultimately reaching the groundwater table.
- ET is defined as the evaporation or transpiration of water from open bodies of water, the unsaturated soil zone, and the shallow saturated zone. Temperature, humidity, wind velocity, soil type, and depth to water are factors that control evaporation rates. Studies have shown that the principal controlling factor in evaporation is depth to water. As depth to water increases, evaporation decreases (Reed, et al., 1952). Transpiration is defined as the uptake by plant root zones and subsequent discharge of water to the atmosphere during growing. Quantifying ET is notoriously difficult because it can vary daily and over short distances, depending on soil types and land use. Oklahoma is especially challenging because of the highly variable temperature and precipitation distributions (Stadler and Walsh, 1983).
- Runoff is that portion of water that becomes part of the surface water hydrologic system; it does not recharge the aquifer nor is it part of the ET process.

3.2 Cimarron River

The Cimarron River and its floodplain, consisting of terrace deposits and alluvial floodplain gravels and sands, is the major hydrologic feature at the Cimarron Site. The headwaters of the Cimarron River are in Union County, New Mexico at an elevation of about 8,000 feet above mean sea level. It flows through areas of Colorado, Kansas, and Oklahoma and terminates at the Keystone Reservoir on the Arkansas River at an elevation of about 850 feet above mean sea level. Land along the course of the river is used mainly for farming, ranching, and residential development. The Cimarron River is a mature river with a well-defined channel and floodplain. The stream bed is generally flat and sandy and the river is bordered by terrace deposits and floodplain gravels and sands (Adams and Bergman, 1995).

3.2.1 River Flow

The Cimarron River is a gaining river over its entire course from Freedom to Guthrie, Oklahoma. In the vicinity of the Cimarron Site and Guthrie, the flow is perennial. Base flow from the alluvial and terrace aquifers and from the Permian sandstone units that border the river is highest in the winter months due to the higher water tables in these aquifers, which result from decreased evapotranspiration. Base flow is lowest from late summer through early winter because water tables are at their low point during that time. Because the Cimarron River is fed mainly by base flow from groundwater aquifers, base river flow in the Cimarron River parallels this seasonal fluctuation in groundwater levels.

From 1974 to 2006, the Dover gage, located approximately 30 miles west (upstream) of the site, recorded from 199 to 2,804 cubic feet per second (cfs) average annual flow rates (USGS, 2007). From 1938 to 2006, the Guthrie gage, located approximately 10 miles east of the site, recorded from 192 to 3,901 cfs average annual flow rates (USGS, 2007a). Adams and Bergman (1995) reported a low-water median flow rate of approximately 100 cfs and a high-water median flow rate of 600 cfs. Flood statistics for the Cimarron River have been compiled by the USGS (Tortorelli and McCabe, 2001) and indicate that peak flows at Guthrie range from a 2-yr flood with a discharge of 26,700 cfs to a 500-yr flood with a discharge of 237,000 cfs. These numbers are in general agreement with the numbers calculated by the USGS (2007b) of 27,800 cfs and 233,000 cfs, respectively, and with the values calculated using PKFQWin, described below. Floods most typically occur in this area in May-June or October, largely as a function of heavy rainfall in upstream portions of the watershed.

The National Weather Service (NWS, 2007) reports that the five highest flow events on the Cimarron River at Guthrie were in 1935, 1957, 1959, 1974, and 1986 and correspond with peak stages of 20.71 feet, 20.50 feet, 18.90 feet, 18.58 feet, and 18.58 feet, respectively. According to the NWS's ranking, Major Flooding is defined as flooding with crests greater than 20.0 feet and Moderate Flooding occurs with crests greater than 18.0 feet. Bankfull Stage, Flood Stage, and Minor Flooding all occur at 13.0 feet; and the action stage is 11.0 feet. The Action Stage as defined by the NWS as the stage at which a NWS partner/user needs to take some type of mitigation action in preparation for possible significant hydrologic activity.

At the Dover gage, the top five flow events occurred in 1986, 1957, 1995, 1982, and 1993 with water cresting at 26.10 feet, 25.70 feet, 23.10 feet, 22.87 feet, and 22.49 feet, respectively. All of these events are characterized as Major Flooding (22.0 feet). Moderate Flooding occurs at 20.0 feet. Bankfull Stage, Flood Stage, and Minor Flooding all occur at 17.0 feet; and the action stage is 15.0 feet.

For two water years in the early 1970s (from October 1970 to September 1972), there was a gage on the Cimarron River at Crescent, which is assumed to have been at the Route 74 bridge. The USGS does not report the stage for this site, but the daily discharges ranged from under 1 cfs to just over 6,000 cfs. These rates compared with the rates presented in **Table 3-1** and suggest that there were no flooding events during these two years and that flows were relatively low.

3.2.2 Statistical Flows

To date, flows for various recurrence intervals have not been developed for the site. Much of the site's response to high flows on the Cimarron River is based on anecdotal observations and lack a quantitative basis. To fill this data gap, an approach was developed to estimate river flows with different recurrence intervals on the Cimarron River at the site. The approach relied upon the use of PKFQWin 5.0.0 (Flynn, et.al, 2005) and historical flows at the USGS Dover and Guthrie Gages. The Dover gage is approximately 30 miles upstream of Route 74; the Guthrie gage is approximately 10 miles downstream of Route 74. Flows at the site were then estimated based on distance from the gages (assuming flow varied linearly with distance).

PKFQWin 5.0.0 is a USGS statistical tool that uses the log-Pearson Type III distribution for extreme event representation and annual peak flow data at each of the Dover and Guthrie to estimate flow events for different recurrence intervals. The background for PKFQWin is based on Bulletin 17B (IACWD, 1982). PKFQWin 5.0.0 is free and can be downloaded at http://water.usgs.gov/software/peakfq.html.

It is acknowledged that there are uncertainties associated with this approach. The use of annual peak flows, for instance, simplifies the dynamics of the river flows. However, in the absence of a gauging station at the site and associated historical data, this approach provides a reasonable estimate of flows with various recurrence intervals. These estimates are summarized in **Table 3-1**.

Critical to understanding vertical recharge through the variably-saturated zone is to estimate the extent of overtopping of the river banks during peak flows. PKFQWin was used to estimate recurrence interval *stage* events (instead of flow); these stage events were then converted to depths based on stage-depth relationships developed from historical actual flow measurement data at each of the gage station websites. Thus, recurrence interval depth-of-flow events were generated for each gauging station and these data were interpolated to give depth data at Route 74 adjacent to the site. Based on an estimated elevation of the river bed at Route 74 (925 feet), recurrence interval flood elevations could be estimated. These depths are summarized on **Table 3-2** and **Figure 3-1** maps the flood plain for three recurrence interval flood events based on these calculations.

Prior to this evaluation, a quantitative evaluation of flows and stages at different recurrence intervals had not been available for the site. This data helps to characterize depth and duration of ponding. To address this need, the above evaluation was completed. Despite some assumptions (regarding flows and stages changing linearly along the river, channel shape, etc.) and inherent contradictions in the results (higher upstream flows than downstream as shown in the shorter recurrence intervals), the estimated flood flows and elevations are considered appropriate to understand site flooding and ponding.

3.3 Recent Hydrologic Events – Site Response

The extreme precipitation and resultant surface water and groundwater events in spring and summer of 2007 provide valuable insight into the site's response to such events. This section will first discuss the data in general; subsequent sections will discuss four events in more detail.

3.3.1 Overview

3.3.1.1 Precipitation

According to the Oklahoma City weather station, between March 1 and August 21, 2007, 40.84 inches of rain fell in a number of intense storm events. This total rainfall represents significantly more than the average annual rainfall of 36 inches per year. A weather website, www.wunderground.com, provided the data to generate the following summary based on data at the Oklahoma City weather station. Rainfall data, recorded daily at the site, is summarized in the last column.

	Actual 2007 Rainfall (inches)	Normal Rainfall (inches)	Deviation from Normal %	Rainfall as measured at site
March	8.02	2.9	177	6.80
April	2.57	3	-14	3.00
May	8.49	5.44	56	6.76
June	10.06	4.63	117	12.62
July	6.31	2.94	115	4.18
August (up to the 22nd)	5.39	1.78	203	4.34
Total	**40.84**	**20.69**	**97**	**37.70**

Figure 3-2 shows the daily precipitation data from the Oklahoma City weather station and the precipitation data from the site. The site precipitation data and the Oklahoma City weather station data are very similar indicating a general uniformity of regional precipitation patterns. Variability within the boundaries of the site is not expected to be significant.

In this six-month period, almost double the normal rainfall fell. Based on the precipitation record at Oklahoma City weather station, the greatest single precipitation event was 3.82 inches (August 19, 2007); this was preceded by 1.56 inches on August 18, 2007. On March 30, 2007 3.5 inches fell, preceded by 1.43 inches on March 29, 2007. Finally, 2.33 inches and 2.08 inches of rain fell on March 7 and 8, 2007, respectively. These precipitation events are the most comparable to a statistically based 24-hour, 2-year precipitation event of 3.3 inches (Rea and Tortorelli, 1999).

Based on site precipitation data, the greatest single precipitation event was 3.65 inches (August 19, 2007). Consistent with the Oklahoma City data, this was preceded by a fairly substantial rainfall of 0.7 inches on August 18, 2007. The rainfall on August 19, 2007 is consistent with the 24-hour, 2-year precipitation event of 3.3 inches (Rea and Tortorelli, 1999). Other high rainfall amounts occurred on June 29, 2007 (2.67 inches) and May 7, 2007 (2.60 inches).

3.3.1.2 Cimarron River Flow

Figures 3-3 and 3-4 show the daily average flow data for the Dover and Guthrie gages between March 1, 2007 and August 21, 2007. Also shown on these graphs is a plot of the median of the daily mean flow calculated based on available historical data. This data gives an indication of the magnitude of the flow events between March and August relative to daily median flows.

The first flow events during this time occurred in late March 2007. According to the flow data, peak flows were on March 30, 2007 in Dover and March 31, 2007 in Guthrie. These high flows were largely attributed to the large rainfall amounts measured at Oklahoma City in late March 2007. In response to this event, Cimarron began taking routine measurements of depth to water at a number of wells in the BA#1 area. Observations were also made with respect to the river's elevation relative to the site and to note if there were any areas of pooling water (due to overtopping or poor drainage). The next sections rely heavily on the data collected and observations made by Cimarron personnel. Unless otherwise noted, precipitation reported comes from the Oklahoma City weather station.

3.3.1.3 Groundwater Elevations

To provide some context for the following discussion and conclusions regarding groundwater it is useful to review concepts from the CSM Rev 01 (ENSR, 2006a) and the Groundwater Modeling Report (ENSR, 2006b). These reports present the site in a regional context and demonstrate that the Cimarron River is a regional discharge boundary. The river receives groundwater from the entire drainage basin, a portion of which must pass through the Cimarron site on its way to the Cimarron River. ENSR's groundwater model results indicate that as much as 50 million gallons of water pass through the BA#1 portion of the site annually (as modeled, ENSR, 2006b) and that more than three times that much pass through the WAA portion of the site annually (as modeled, ENSR, 2006b).

Three significant observations were made based on the groundwater data collected.

- Changes in groundwater elevations observed in wells in low permeability soils (Transition Zone and Sandstone) were similar regardless of whether or not the data was collected seasonally or almost daily. This indicates that, while gradients and fluxes in these soils may change in response to transient hydrologic events, the duration and magnitude of the changes is expected to be in the order of days or weeks and that the flux increases over this time is small relative to the overall flux of groundwater across the site annually.

- In the Alluvium wells, seasonally-collected groundwater elevation data did not capture the highs and lows that were observed when data was collected almost daily. The observed groundwater elevation rises and falls indicated that water levels change in parallel, yielding parallel gradients. Rises were observed to occur over the course of a few days, perhaps weeks. The increases in groundwater fluxes over these short time frames are not expected to be significant relative to the overall flux of groundwater across the site annually.

- An evaluation of groundwater data collected from April to August 2007 indicates that the changes in hydraulic gradients and flow directions result in small changes relative to the overall water budget of the site. The duration of these changes are on the order of days, perhaps weeks. Given this, rates and directions of contaminant transport are also unlikely to be significantly affected by transient events.

Figure 3-5 depicts the rise and fall of groundwater elevations from early April to August 20, 2007. **Figure 3-6** shows the locations of these wells. The groundwater response was measured routinely in 10 wells located in the BA#1 area. Three of these wells, TMW-02, TMW-08, and TMW-21, are screened in Sandstone B (red lines, red dots). Five wells are screened in Alluvium: 02W16, 02W24, 02W36, 02W43, and TMW-13 (green lines, green dots). Two wells are screened in Transition Zone soils: TMW-05 and TMW-09 (blue lines, blue dots).

Overall, the rise and fall of groundwater elevations indicate that the alluvial wells are most responsive to hydrologic events. The transition zone wells and two of the three Sandstone B wells were not as responsive as alluvial wells. The total head change seen over the period of record ranged from approximately 3.4 feet to just over 8 feet. The smallest overall changes were seen at the wells screened in transition soils and in two (TMW-02 and TMW-08) of the three sandstone wells. TMW-21 is fairly responsive, relative to the other Sandstone B wells, but its response is less than the alluvial wells. The greatest single change (8.08 feet) was observed at 02W43 between August 17 and 20 of 2007.

Water level data had been collected previously at these wells and formed the basis of the calibration data set for the groundwater model (ENSR, 2006b). There are some interesting comparisons between the data collected in September 2003, December 2003, August 2004, and May 2005 to the data recently collected (quasi-daily). The following table summarizes the groundwater changes over the long term and over the spring and summer of 2007.

		Maximum groundwater change (ft) based on data from September 2003, December, 2003, August 2004, and May 2005	Maximum groundwater change (ft) based on data collected from April to August 2007
Sandstone B	TMW-02	0.97	3.82
	TMW-08	3.24	3.6
	TMW-21	7.88	7.91
Transition Zone	TMW-05	3.82	4.44
	TMW-09	3.6	4.38
Alluvial	02W16	2.39	7.03
	02W24	2.43	7.82
	02W36	2.29	7.84
	02W43	2.18	8.08
	TMW-13	2.11	7.81

The data indicates that at two of the Sandstone B wells (TMW-21 and TMW-08), recent fluxes in groundwater changes are consistent with what may be observed based on less frequent measurements. This is consistent with what was seen at the Transition Zone wells; long-term differences are consistent with short-term differences. In contrast, water level changes in the alluvial wells based on long-term measurements were far smaller than the changes seen over the spring and summer of 2007. At TMW-02, seasonal water level differences were also much smaller than the spring-summer 2007. It is possible that TMW-02 is screened across soils with different hydraulic conductivities compared to TMW-21 and TMW-08 and thus, is less responsive to short-term events. The graph of water elevations over time (**Figure 3-5**) suggests that water levels at TMW-02 were not as susceptible to precipitation events as at other wells.

The general consistency in water level changes in the Sandstone B and Transition Zone wells suggests that seasonal, infrequently recorded data tends to be as representative as short-term water level changes, even after extreme events such as those seen during the spring and summer of 2007. Alternatively stated, water level fluctuations are no greater whether they are measured frequently or infrequently. This is a significant observation as it implies a fairly stable flow field in the sandstone and transition soils. Water level changes resulting from transient hydrologic events are muted by the relatively low permeability soils such that they are consistent with longer term (seasonal) hydrologic events. This is consistent with what had been stated in the CSM Rev 01 (ENSR, 2006a): "the hydraulic gradients and flow directions do not change significantly over time. Therefore, rates and directions of contaminant transport are also unlikely to change significantly."

In the alluvial wells, only 2 to 2.5 feet of groundwater elevation relief were observed based on the seasonal data, but up to 8 feet of elevation relief were recorded based on the quasi-daily data. When considering the gradients and fluxes, however, it is the relative elevation differences between the wells that are important. In this case, whether groundwater elevations were low or high, for the most part the elevation differences between the most distant upgradient alluvial well (TMW-13) and the other alluvial wells were consistent – indicating parallel gradients.

The exception to this was between alluvial wells TMW-13 and 02W43 where the elevation differences based on seasonal data tended to be a few tenths of feet while the elevation differences based on the quasi-daily data tended to be on average approximately 0.6 feet (three times greater than the average elevation difference of 0.2 feet based on the seasonally-collected data). Elevation differences of 0.6 feet (between TMW-13 and 02W43) represent a two to three-fold increase in hydraulic gradient compared to the gradients in the alluvium reported in the CSM Rev 01 (ENSR, 2006a) and based on the seasonally collected data. The greatest elevation difference recorded based on the quasi-daily data was 1.14 feet, representing an approximate five fold increase in gradient. When elevation differences were up around one foot (between TMW-13 and 02W43), they persisted for at most eight days. In the context of evaluating water balances, the incremental increase in flux during periodic short term increases in gradient is small relative to the annual flux site-wide.

In summary, in the Sandstone B and Transition Zone soils, transient hydrologic events as seen during the spring and summer of 2007 are not expected to result in changes to the groundwater gradients and fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This suggests that groundwater elevations in Sandstone B and Transition Zone soils are fairly stable and that the zone of variably-saturated soils is, in general, thin relative to the zone of variably-saturated zone soils in the alluvial soils. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events; however, elevations generally responded uniformly indicating no change in groundwater gradients. Changes in flux will be small relative to the total water budget for the site. The exception to this was that some data suggested periodic change in groundwater gradients between TMW-13 and 02W43. These changes lasted at most eight days; this short duration may result in short-term increases of flux, but relative to the total water balance, these increases are considered insignificant.

3.3.1.4 Groundwater/Cimarron River Interaction

This section deals with the hydraulic connection between the river and the aquifer via the alluvial soils. **Figure 3-7** shows the daily water level data collected at 02W48 and TMW-24 using pressure transducers. For reference, the locations of these wells are shown in **Figure 3-6**; these wells are the most downgradient wells and are approximately 200 feet upgradient from the river bank. The most significant observation made based on this data is that there is no direct hydraulic connection via the aquifer between river water levels and groundwater elevations at or upgradient of TMW-24 and 02W48. Because there is no direct hydraulic connection via the aquifer, there are no anticipated water quality impacts of river water on groundwater at or upgradient of TMW-24 and 02W48. It is important to note that river water that overtops the river banks may impact groundwater elevations and water quality anywhere it can access via low-lying topography.

Because of a transducer malfunction, there is an incomplete data record for TMW-24. However it is clear from the available data that the water levels in TMW-24 and 02W48 closely parallel one another. By comparing the precipitation events to the groundwater response, it is also clear that the water levels respond quickly and in concert with the precipitation events.

In contrast, **Figure 3-8** shows the same transducer data plotted with the Guthrie flow data. The groundwater hydrographs and surface water hydrograph are not in concert. Where there are groundwater peaks, there are hydrograph troughs and vice versa. This inconsistency indicates that at these well locations, groundwater levels are not impacted by river water levels (via alluvial soils). If there was a direct hydraulic connection between the surface and groundwater at this location, the groundwater conditions would mirror surface water conditions, though with a time lag as the pressure wave of water moved through the porous media. This pattern is not observed.

As the findings indicate, there are no anticipated water quality impacts to the groundwater from river water, independent of possible impacts from river overtopping. Note that this conclusion is in agreement with what was presented in the CSM Rev 01 (ENSR, 2006a) wherein it was shown that river water quality and groundwater quality were, based on the preparation of stiff diagrams, quite different. It can be said that the river water levels and/or quality, independent of overtopping conditions, will not impact groundwater levels or quality at or upgradient of TMW-24 and 02W48.

3.3.2 Event-based discussion

3.3.2.1 Late March and April 2007

Between March 22 and March 30, 2007, 6.52 inches of rain fell at the Oklahoma City weather station (3.90 inches at the site). This rainfall caused a peak flow of 8,720 cfs at the Dover gage on March 31, 2007 and a peak flow of 24,400 cfs on March 31, 2007 at the Guthrie gage. At the Dover gage, flows returned to rates consistent with the median of the daily mean values about five days later on April 5, 2007. Flows at the Guthrie gage dropped down to 829 cfs on April 12, 2007, but never reached median values for that date (528 cfs).

A few days after the river flows dropped back down to median or near-median values, they rose again as a result of another April precipitation event. On April 10, 2007 0.09 inches fell, on April 13, 2007 0.86 inches fell, and on April 17, 2007 0.77 inches fell. For comparison, the site gage recorded 1 inch, 0.8 inch, and 0.65 inch on April 13, 14, and 17, 2007, respectively. The cumulative effect of this precipitation resulted in a peak flow of 6,420 cfs at Dover and 7,890 cfs at Guthrie; both peaks were on April 15, 2007. Flows returned to rates consistent with the median flow rates on April 21 and on April 30, 2007.

The shape of the hydrograph indicates that peak flows lasted one day with a steep increasing limb meaning that the response of the river to precipitation was fairly rapid, over one to two days. Flows decreased back down at lower rates as suggested by the less steep declining limb of the hydrograph. At the Dover gage, it took 5 to 6 days to return to median flow rates. At the Guthrie gage, it took 12 days and 15 days, respectively, for each of the two events to reach the lowest flow rate. The lengthy recovery rate is related to the large watershed that the gage at Guthrie represents. Also, there are contributing stream flows between Dover and Guthrie that, because of a different peak along those reaches, could have slowed the rate of overall flow rate decline.

According to PKFQWin calculations, a flow rate of 8,720 cfs at the Dover gage corresponds to a recurrence interval of approximately 1 year and corresponds approximately to a depth of flow of 5.8 feet (**Tables 3-1** and **3-2**). At Guthrie a flow rate of 24,400 cfs corresponds to a recurrence interval of less than 2 years and greater than 1.5 years and to a depth of flow of 12.2 feet. Based on these ranges of flows and depths, it is expected that the depth of flow at the site (Route 74) would be around 8.5 feet and flows in the range of 10,000 to 20,000 cfs depending on the contributions of other stream flows and bank storage capacity, among other factors. This rate and depth of flow is expected to have resulted in high flows approaching bankfull, but not necessarily significant overtopping. A photo taken at the Route 74 bridge (looking south, at the site) on April 2, 2007 confirms this understanding (**Figure 3-9**); a corresponding picture showing typical dry conditions is also shown in **Figure 3-9**. Though there was no observed overtopping of the banks at the site, there were some areas of the site where rainwater ponded and persisted for several days. **Figure 3-10**, taken on April 2, 2007 shows the flood plain area of BA#1; a corresponding picture showing typical dry conditions is also shown in **Figure 3-10**.

Ponded water occurs when a) topography is relatively flat or there is a low lying area in which water can collect and/or b) because of poorly draining soils, such as clay. As discussed in Section 2.3 there are some silty clays in the flood plain which may restrict vertical flow. When water ponds, some portion will evaporate, some may runoff, and some portion will drain vertically through the underlying soils to the root zone and potentially to the water table. When this occurs, the vertical flow rate is equal to the vertical hydraulic conductivity of the underlying soils.

Figure 3-5 shows the groundwater response to these rainfall events. In early April 2007 water levels in the wells were either declining or fairly steady. Small water level rises were observed starting on April 13, 2007. Given that there was a fairly immediate groundwater response to mid-April rainfall, occurring between April 10 and 14, 2007, it would appear that the rises are attributable to the mid-April rainfall as opposed to attributable to the late March/early April rainfall.

Among the wells, the rises in groundwater elevation between April 13 and April 18, 2007 ranged from 0.13 to 2.5 feet. The highest response was at TMW-21, a well screened in Sandstone B located in the uplands near the original burial trenches. Because of the distance to the river, the water table fluctuations at this location are assumed to be entirely attributable to site precipitation. The lowest response observed was at TMW-02, also located in the uplands in the former burial trench area. Response at TMW-08, a Sandstone B well located downgradient of TMW-02, was also low (0.31 feet). The muted responses of two of the three upland wells are attributable to heterogeneities in the Sandstone B formation.

In the transition zone wells, groundwater levels changed 0.68 and 0.53 feet. Responses in the alluvial wells were around one foot of groundwater elevation increase. Assuming that the water level response at TMW-21 is attributable entirely to rainfall, and that the rises in the alluvium are less than the responses seen at TMW-21, it can be concluded that the responses in the alluvium are also entirely attributable to rainfall. That is, changes in river elevation do not appear to be impacting groundwater elevations. This is true even at the most downgradient well 02W43, where elevations mirror patterns seen at other wells, not patterns seen in the river. This conclusion is confirmed by the transducer data collected at wells even closer to the river (see Section 3.3.1.3).

3.3.2.2 Early May 2007

There were several small rainfall events between mid-April 2007 and early May 2007. Based on data from the Oklahoma City weather station, five days of rainfall began on May 7, 2007 (2.33 inches) and continued through May 11, 2007 (2.06, 0.02, 0.29, 0.31 inches, respectively). According to site precipitation measurements, 3.9 inches of rain fell between May 7 and May 9, 2007. This rainfall resulted in rises on the Cimarron at Dover to 12,300 cfs (May 8, 2007) over the course of two days and rises to 33,700 cfs (May 9) at Guthrie over the course of three days. In the case of Dover, flow rates returned to median values in about six days. Even 20 days later, flows at Guthrie had not returned to median values and then flows went up again to 4,410 cfs on June 2, 2007 in response to a smaller rainfall event at the end of May 2007. Flows at Dover also responded to this late May rainfall by rising to 1,830 cfs also on June 2, 2007. This flow is less than the median flow for that date.

According to the PKFQWin calculations, 12,300 cfs at Dover corresponds to a 1.25 year recurrence event and 33,700 cfs at Guthrie corresponds to a 2.3 year recurrence event. Based on **Table 3-1** it is therefore estimated that flow at the site (Route 74) was likely around 23,000 cfs, a flow with recurrence interval of between 1.5 and 2 years. **Table 3-2** indicates that a river elevation corresponding to this flow may result in some bank overtopping depending upon factors such as antecedent moisture conditions, local scale topography, and bank storage availability. **Figure 3-11** is a photo taken on May 15, 2007 showing the river level relative to the banks; a corresponding picture showing typical dry conditions is also shown in **Figure 3-11**.

According to field notes, water was ponded around well 02W16 on May 9, 2007. **Figure 3-12** shows that ponding was extensive in the lower elevations of BA#1; a corresponding picture showing typical dry conditions is also shown in **Figure 3-12.** The extent of flooding looks similar to that observed in April 2007 (**Figure 3-10**). The ponding occurred after approximately 4-5 inches of rain. Observations made by Cimarron staff indicate that during high flow events, low-lying small drainage features will flood with Cimarron River water; in some instances, river water can reach as far south as the escarpment. For most of the storm/flow events observed over the spring and summer of 2007, ponding in the vicinity of BA#1 is attributed to both rainfall and river water.

Measurements of ponded depths were made at four locations (wells 02W05, 02W16, 02W22, and a stake just east of TMW-13) several times through mid-May. The data indicated that ponding was as deep as 19 inches and lasted as long as 16 days. Over this time, the average depth of ponding ranged from approximately 6 to 10 inches, depending on location and duration of ponding. By plotting ponded depth over time, the rate at which ponding decreased was estimated to be around 1.25 inches per day; this rate includes infiltration, runoff, and evapotranspiration as mechanisms for water removal. This rate applies when ponding exceeded approximately one foot. As ponding decreased, the removal rate appears to slow; this could be attributed to a reduced infiltration rate because of less hydrostatic head, less runoff, and/or reduced infiltration.

Groundwater rises were most pronounced in the wells screened in the alluvium (**Figure 3-5**). Over four days the average rise over all five alluvium wells was 6.55 feet and ranged from 6.13 to 6.94 feet. At TMW-21 water levels rose just over 4 feet. Water levels rose 0.17 and 1.22 feet at TMW-02 and TMW-08, respectively. Differences in response are attributed to local-scale heterogeneities. In the transition wells, water levels rose approximately 2.4 feet. However, the water levels at TMW-09 declined more slowly than the water levels at TMW-05 suggesting that the conductivity may be less at TMW-09.

3.3.2.3 Mid-June to Late July 2007

This period represents a protracted period of ongoing rainfall events. The total rainfall over this period (June 10 to July 31, 2007) was 16.2 inches, a value nearly half the normal total annual rainfall. **Figure 3-2** shows that there was no singularly high rainfall event, rather a series of heavy rainfalls day after day. Site precipitation data over the same time period was 15.68 inches.

The river responded accordingly by registering increased flows that were persistently high. Peak flows at Dover were recorded on June 16, 2007 (16,700 cfs), June 20 and 21, 2007 (10,200 cfs), June 30, 2007 (29,800 cfs), and July 14, 2007 (29,100 cfs). Unlike responses earlier in the year, some of the high flow peaks during this time occurred over two or more days. This is expected; the persistent rainfall results in accumulated runoff over several days. Peak flows at Guthrie were recorded on June 15, 2007 (31,200 cfs), June 21, 2007 (12,800 cfs), June 30, 2007 (61,000 cfs), and July 14, 2007 (40,300 cfs). It is interesting that Guthrie peaked on June 15, 2007, earlier than Dover did on June 16, 2007. This data may reflect large flows from tributaries influencing Guthrie before Dover. Spatial differences in precipitation may also cause the earlier peaks at Guthrie as compared to Dover. As with Dover, the peaks were spread over several days, as opposed to one or two days as in the events earlier in the spring.

The Dover flow of 29,100 cfs corresponds to a recurrence interval flow event of approximately 2.3 years. The Guthrie flow of 61,000 cfs corresponds to a recurrence interval flow event of approximately 7.5 years. Based on these flows, it is estimated that the flow at the site (Route 74) was approximately 45,000 cfs, which corresponds to an estimated flood elevation of approximately 939.0 feet elevation. It is expected that the banks would be overtopped and the flood plain would experience some flooding at this elevation. **Figure 3-13** (June 29, 2007) is a photo of the site from the Route 74 bridge; a corresponding picture showing typical dry conditions is also shown in **Figure 3-13**. Compared to similar photos taken in April 2007 (**Figure 3-9**) and May 2007 (**Figure 3-11**), this photo shows that the water is considerably higher and has obscured a sandy bank near the bridge's southern abutment previously visible. **Figure 3-14** shows considerable flooding (June 29, 2007), whether from accumulated precipitation or bank overtopping, in the Western Alluvial Area; a corresponding picture showing typical dry conditions is also shown in **Figure 3-14.**

Given the persistent high flows and the photos of the Western Alluvial Area, ponding is expected to have occurred in the low lying areas site-wide. Again this ponding is attributed to both intense, persistent rainfall as wells as inundation along low-lying drainage ways across the floodplain. Field notes suggest that there was ponding near 02W16 for at least a week.

Similar to early May 2007, the biggest groundwater responses were observed in the alluvial wells and in TMW-21. In the alluvial wells, there was an average increase of 6.33 feet between June 13 and June 29, 2007. At TMW-21 the water level increase was 6.00 feet. Water level increases at TMW-02 and TMW-08 were 1.24 feet and 2.73 feet, respectively; this pattern is consistent with what was discussed previously. Approximately three feet of water level increase was observed at the transition wells. Consistent with the persistent precipitation and high river flows, groundwater elevations remained high for about a month. Sometime around mid-July 2007, groundwater elevations began dropping and dropped to the lowest they had been since the measurements began in early April 2007. Similarly, flows at Dover dropped to levels consistent with median flow rates and Guthrie flows also receded, but not as low as the median rates.

3.3.2.4 Mid-August 2007

Based on data from the Oklahoma City weather station, between August 17 and 19, 2007, 5.39 inches of rain fell, with 3.82 inches falling on August 19, 2007. No precipitation fell at the site on August 17, 2007. At the site, on August 18, 2007, 0.69 inches fell and on August 19, 2007 3.65 inches fell. The resultant flows at Dover were remarkably low (1,870 cfs on the 19) even though this amount of precipitation had previously resulted in considerably higher flows. The low flow is attributed to spatial variability in precipitation amounts; in fact other weather stations reported considerably less precipitation over that same three-day period (0.39 inches at Enid Vance AFB). Guthrie, on the other hand, saw a substantial peak over two days to a peak flow of 33,700 cfs. Flows promptly declined to approximately one-tenth of that flow, but another rainfall event on August 24, 2007 (trace at OKC, but 0.37 inches at the site and 0.53 inches at Enid AFB) and flows appeared to be rising again.

A flow rate of 1,870 cfs at Dover is so low there is no calculated recurrence interval for it. A flow of 33,700 cfs is consistent with a 2 to 2.3 year recurrence interval flow event. Based on the spatially variable rainfall, it is difficult to estimate flows at the site (Route 74). Anecdotal evidence indicates that river water likely inundated the low-lying drainage features in the flood plain, but that most of the flood plain was otherwise dry. The flow at the site is estimated in the 5,000 to 10,000 cfs range.

In the wells screened in the alluvium, dramatic water table rises were seen between August 17 and 20, 2007 equaling, on average, 7.89 feet. This was the largest rise observed during the measurement period to date. Interestingly, the rises at TMW-21 have typically been consistent with alluvial well rises, but for this event, only slightly over a one-foot rise was observed and the peak occurred later than the peak in the alluvial wells. Unlike the previously discussed events where precipitation appears to be spatially well-distributed, for this event, the precipitation appeared to be spatially variable. Because of this, the rises in groundwater during this event are more of a reaction of the local rainfall depths as opposed to the accumulated impact of regional increases in groundwater as a result of regionally distributed precipitation. Groundwater rises in the other wells screened in Sandstone B were small, only 0.28 and 0.36 feet. Water level rises in the transition wells were 2.63 feet and 1.20 feet at TMW-05 and TMW-09, respectively. Unlike other events where the water levels in these two wells tended to parallel one another, in this event, the response at TMW-05 was more than double that of TMW-09. Similarly the decline of water levels at TMW-05 was rapid.

3.3.3 Event-Based Summary Observations

The precipitation, stream flow, and groundwater elevation data collected over the spring and summer of 2007 provide a unique opportunity to observe how the site responds to individual storm events, individual extreme events, and a series of extreme events. Cimarron will continue to collect this data at this time. Based on recent events, the following observations can be made:

- A total of 40.48 inches of rain fell between March 1and August 21, 2007. This represents an almost 100% increase over typical rainfall during the same time period, and roughly 5 inches above the normal amount received through the course of an entire year. Site precipitation data is consistent with data from the Oklahoma City weather station.
- Rainfall events resulted in a maximum flow rate at the Dover gage of 29,800 cfs on June 30, 2007 and resulted in a maximum flow rate at the Guthrie gage of 61,000 cfs also on June 30, 2007. It is estimated that during these flows, the flow rate at the site, Route 74, was approximately 45,000 cfs and resulted in flood elevations that caused low-lying drainage features to be inundated and river water to move into the floodplain as far south as the escarpment. This type of flooding (i.e., inundation of low-lying areas) was the typical mechanism for river water to move into the floodplain; there was no gross flooding of the floodplain wherein the entire flood plain was under water.
- Almost all of the events observed resulted in some amount of ponding around the low-lying poorly drained areas in the flood plain, for instance around well 02W16. The mechanism by which water ponded in the low-lying areas of BA#1 is a combination of factors: low permeability soils, intense rainfall, runoff from upland areas, and river water inundation along floodplain drainage ways.
- The water level data collected by the transducer at 02W48 and TMW-24 both located approximately 200 feet from the river showed groundwater hydrographs that are strongly influenced by precipitation and are not influenced by a hydraulic connection via the aquifer with the river. Stiff diagrams presented in the CSM Rev 01 identified that water quality at 02W48 and TMW-24 is consistent with Sandstone C and Alluvial well waters, respectively - that is, uninfluenced by river water quality. Data indicate that, independent of overtopping conditions, high river elevations will not impact groundwater elevations or water quality in the plume area as currently mapped (ENSR, 2006a).
- In general, based on groundwater levels measured in the Sandstone B and Transition Zone wells, the transient hydrologic events seen in the spring and summer of 2007 did not result in changes to the groundwater gradients and fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This conclusion indicates that groundwater elevations in Sandstone B and Transitions Zone soils are fairly stable. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events, however elevations generally responded uniformly indicating no change in groundwater gradients. Fluxes may change, but the largest changes lasted at most eight days; this duration may result in short-term increases of flux, but relative to the total water balance and the scope of the study, these increases are insignificant. Note that the zone of variably-saturated soils in the transition and upland areas is, in general, thin relative to the variably-saturated zone in the alluvial soils.
- Rainfall events were typically frontal storms that affected the region and resulted in regionally uniform responses in river flows and groundwater elevations. The most recent rainfall event was not as spatially uniform resulting in almost no flow response in Dover, but a fairly substantial response in Guthrie. In the groundwater, alluvial wells responded consistently with other events, but TMW-21, a Sandstone B well, registered a relatively low response. This suggests that the Sandstone B may be most responsive to regional events and less responsive to local scale rainfall events. The water levels

measured at wells screened in Sandstone B seemed most sensitive to geologic heterogeneities compared to the other wells.

4.0 Hydrologic Modeling

The specific objective of this report is to characterize the impacts surface water hydrology may have on the water budget of the variably-saturated soils and specifically on the recharge to groundwater. Thus far, the potential inputs to the variably-saturated zone have been characterized. Specifically, the report has discussed:

- General, specific, and extreme rainfall events;
- Land response to the rainfall events, including soil types that will control runoff and drainage, thus potential for ponding; and
- River response to these rainfall events, including bank overtopping.

It is the objective of this report to better understand the water budget of the variably-saturated zone and quantify potential groundwater recharge based on a number of rainfall, ponding, and river overtopping scenarios. It is the water that migrates to the water table, or recharge, that has the potential to impact the fate and transport through the variably-saturated zone.

The HELP (Schroeder, et al., 1994) model was chosen as it provides a robust, relatively simple method for evaluating the water budget of the variably-saturated zone including the discharge of water out of the variably-saturated zone. This discharged water becomes the recharge water to the groundwater system. There are other models and tools that may have performed the task equally well. However, some of these other models require sophisticated inputs and as the inputs become more sophisticated and assumptions are made to accommodate unknowns, the uncertainty of the model results increases. The HELP model is considered an appropriate tool to complete the evaluation given the objectives of this hydrologic evaluation.

The fate and transport component of the evaluation is discussed in the Groundwater Decommissioning Plan portion of the Site Decommissioning Plan (ARCADIS, March 2008) and will be used, in part, to support a remediation design.

This section provides a conceptual discussion of the hydrology, which will set the stage for model runs.

4.1 Conceptual Model

As discussed in Section 3.0, rainfall is the primary input to the water budget of the variably-saturated zone. Once it has fallen, water will either run off, evaporate, or soak into the ground. Once in the ground, it can either be taken up by transpiration or it will bypass the root zone and reach the water table. Depending on the depth to water, evaporation may occur directly from the water table to the atmosphere.

How water gets partitioned to any of these components (runoff, ET, recharge) is dependent on intensity and duration of rainfall, land use, and soil properties. Also, when rainfall is especially intense or when rainfall results in river flows that cause inundation, water can pond on the land surface. This ponding results in a different boundary condition as the infiltration rate to the subsurface is controlled by soil properties and ponding characteristics, not necessarily rainfall rate. It should be noted that for the Cimarron site, ponding likely occurs as a result of a combination of precipitation and/or upland runoff and/or river inundation.

In quantifying the recharged water flux through the variably-saturated zone, there are conceptually three scenarios to consider:

1. Vertical infiltration due to rainfall;

2. Vertical infiltration due to ponded water. The mechanisms by which ponded water may occur and persist include, in some combination:
   a. Low permeability soils.
   b. Low-lying areas that may be inundated during high river flows.
   c. High intensity, long-duration rainfall.
   d. Runoff from upland areas.
3. Increased groundwater elevation as a result of increased river stages.

The first two scenarios are explored using the HELP model in the sections that follow. The evaluation of groundwater rises as a result of river stage rises did not require modeling and is discussed in Section 3.3.1.4.

4.2 Introduction

The use of the HELP model provided a means to evaluate how rainfall is partitioned into evapotranspiration, runoff, storage, and recharge. The HELP model was originally developed by the EPA (Schroeder, et al., 1994) to conduct water balance assessments of landfills, cover systems, and solid waste disposal containment facilities. However, the conceptual and mathematical basis of the model is not exclusive to landfill designs. The model can be used to evaluate water balance for any variably-saturated soil system.

The model uses weather and soil data and solution techniques that account for the water balance components, including surface storage, snowmelt, runoff, infiltration, ET, vegetation, soil moisture, and vertical drainage. Based on inputs, the model calculates the amounts of runoff, ET, and drainage that may occur through a given soil thickness.

The specific inputs used for HELP are described in detail in the Users Guide. Input and output files for each of the simulations presented in the following sections are included in the attached CD-ROM. In general, the two primary classes of inputs include:

- Weather data, including ET data, precipitation data, temperature data, and solar radiation data. In many instances modeling relied on a database and on model guidance to help select inputs for these values. The HELP model includes a tool to generate synthetic precipitation data based on a database of climatological data; this synthetic precipitation data was used in the simulations as well as measured precipitation data.
- Soil data, including area and thickness, soil characteristics, and runoff curve information. Site-specific data were used as inputs. Default values were used for some values for which site-specific data are not available.

Output from the model is essentially a water budget for the variably-saturated zone. Output can include daily, monthly, and yearly summaries of ET, runoff, and recharge proportions that make up a precipitation input. For the base-case simulations (Section 4.3.1), the yearly summaries were of primary interest as they provided confirmation that the model was behaving consistently with the conceptual model of site hydrology. For event-based simulations daily data were output and summarized so that recharge could be calculated based on an extreme precipitation event.

4.3 Simulations

4.3.1 Base-case simulations

The purpose of the base case run was to see how the water balance simulated by the model compared to the understanding presented in Section 3.0. For the first simulations, model inputs and outputs are provided. Discussion of subsequent simulations will then discuss only the changes in inputs from the base case. **Table**

4-1 lists all the input parameters and output for the base case runs. Site-specific input parameters were used when available; default values were used in lieu of site-specific values, when site-specific values were not available.

In the first base case simulation, synthetically-generated precipitation data was used. Based on these input parameters, the output indicates that precipitation was on average 27.47 inches per year with a range of 20.50 to 35.97. This range seems a little low compared with what OCS presents for Logan County of 33 to 36 inches per year, but is considered reasonable. Model output indicates that recharge to the water table (percolation/leakage through Layer 2) was on average 1.25 inches or approximately 4.5% of the total precipitation. This rate is low relative to that presented by Adams and Bergmann (1995) who suggested that recharge represents 8% of the total precipitation. However, their estimate may have been based on soils that did not include as much silt and clay as have been simulated here. Furthermore, the ET was simulated to be 95.5% of total precipitation, a rate consistent with expectations.

For comparison purposes a second base case simulation was run where actual rainfall observations were used as model input. These rainfall observations were made at the Oklahoma City weather station from 2002 to 2006 (5 years). Note that the Oklahoma Water Resources Board considers these years to be drought years because of the lower than normal precipitation rates (OWRB, 2007). The change to precipitation input represents the only change in the input values. The model simulation output indicated that the annual average precipitation was 27.47 inches per year with a range of 22.00 to 36.62 inches per year. The simulated recharge rate was 6.9% (range from 1.5-10.1%) and the ET represented on average approximately 93% of the total rainfall. The differences in recharge rates are attributed to the more natural rainfall patterns as compared to the synthetic precipitation data. This recharge rate is consistent with the 8% presented by Adams and Bergmann (1995).

Finally, for further comparison, the 2007 (through August 20) precipitation data was added to the 2002-2006 series and the model was re-run to see how the extreme events of 2007 impacted the model output. This run indicated that recharge was dramatically higher than other years, 29.2% (approximately 13 inches of the approximately 44 inches of precipitation). These results indicate that the plants were obtaining sufficient water such that any additional water could flow vertically past the root zone to the water table. ET was reduced to around 74% compared to a higher percentage in other years.

These base case runs provide a frame of reference for the response of the model. The following runs will build on this understanding to explore hypothetical extreme events.

4.3.2 Simulate recharge based on site soil variability

This series of model runs explored the variability in recharge depending on soil type. There were three main soil types to consider. Note that the soils of interest are those between the land surface and the water table, not below the water table. Silty-clay underlain by sand is prevalent in the alluvium. A mix of silt and clay with a relatively low percentage of sands, but no underlying sands is typical of soils at transition wells and some upland wells. A few locations indicate as much as five feet of unsaturated fill; these are located in the uplands near the former burial trenches.

Table 4-2 shows that though there are differences in recharge rates in the model output based on varying the input soil types, the recharge rate variations are relatively small and fall within the general understanding of the relative portion of precipitation that actually recharges the aquifer on an annual basis.

4.3.3 Simulate recharge based on extreme precipitation events

The next series of simulations evaluated recharge rates after a single extreme precipitation event. Depth-duration-frequency maps (Rea and Tortorelli, 1999) were used to estimate extreme precipitation depths; these are summarized on **Table 4-2**. For these simulations, soil types were assumed to be consistent with the alluvial soils in the base case. For the 24-hour duration events, the precipitation rate was applied to a hypothetical July 1 of the sixth year of precipitation, which was preceded by 5 years of measured rainfall inputs. In the sixth year, precipitation data for the rest of the year was synthetically based to provide average, representative conditions. For the 7-day duration events, the precipitation rate was applied to a hypothetical July 1 through 7 of the sixth year of precipitation, which was preceded by 5 years of measured rainfall inputs. In the sixth year, precipitation data for the rest of the year was synthetically based to provide average, representative conditions.

Recharge was simulated to total 0.41 inches over the 30 days following a 24-hour, 2-year storm event of 3.3 inches (Rea and Tortorelli, 1999). The 24-hour, 500-year storm event of 10 inches yielded a model estimate of 5.94 inches of total recharge over the 30 days following the storm event. It should be noted that for some of the most intense storm events such as the 24-hour, 500-year event, ponding is simulated to occur. Ponding under these scenarios is assumed to be due entirely to precipitation; this scenario is unlikely as the river would also be responding to such rainfall and likely to overtop and create ponding. These numbers are intended to give a frame of reference for site response, not necessarily to be precise. Details of ponding are discussed in the next section.

Table 4-2 shows the results of these model runs. As expected, the greater the rainfall, the greater the recharge, though the intensity of the storm was also important. The recharge from the 24-hour precipitation events tended to peak quicker than the 7-day precipitation events, which is consistent with the differences in intensities of rainfall events. It is interesting to note that a 10-inch rainfall over 24 hours produces a similar recharge rate to a 12-inch rainfall event over 7 days.

4.3.4 Simulate recharge based on impacts of ponding

Conceptually, ponding on the land surface occurs because the mechanisms for water removal (i.e., runoff, recharge, ET, and removal to storage) do not cumulatively happen at a rate as fast as water can accumulate and/or the ponded area is replenished via upland runoff, additional precipitation, or ongoing inundation. Based on the HELP output, a daily water balance can be calculated in which runoff, recharge and ET are subtracted from precipitation. When the result is negative, it indicates that the water removal mechanisms are greater than the precipitation rate. When the result is positive, it indicates that the there is "residual water" for that day (i.e., precipitation > runoff + recharge + ET). This residual water is defined as the surplus water that includes both water that goes to storage and the water that can be considered ponded water. HELP output does not distinguish between the two. If steady state is reached – as demonstrated by a constant recharge rate – storage in will equal storage out and any residual water can be assumed to be entirely ponded water.

When HELP calculates residual water the program assumes that pressure head is uniformly dissipated in the low permeability layer (i.e., land surface) that is restricting the flow. The recharge rate is then calculated based on a hydraulic gradient and unsaturated hydraulic conductivity. The hydraulic conductivity is a function of soil water content, residual water content, and saturated soil water content. The hydraulic gradient becomes a function of the depth of ponded water. Thus, the recharge rate is a function of the variably unsaturated hydraulic conductivity and the depth of ponded water.

In relation to infiltration of water through the variably-saturated zone and ultimately to the groundwater, the process by which the ponded water recharges the groundwater is the same whether ponding occurs from excessive precipitation or from inundation of low-lying area. The critical factors for calculating recharge when ponding occurs are the depth of ponding and the duration of ponding.

The HELP model was used to evaluate the recharge depth given a scenario where water may pond on the land surface. Ponding in the alluvial area was observed several times during the 2007 period. Observed ponding lasted from a day or two to as much as 16 days. Average ponding depths were estimated to be between 6 and 10 inches over the days in which ponding occurred. These recent observations were used as a basis for formulating an appropriate scenario and simulating ponding and thus, estimating recharge to the groundwater table using the HELP model.

Uniform daily precipitation depths were input to the HELP model to achieve a variety of ponded depths. In general, steady state ponded depths were reached within a few days of the beginning of rainfall. Recharge rates that result from ponded water were dependent on the depth of ponded water. Based on the observations, a ponding depth was conservatively set to 1 foot and was simulated to last as much as 14 days. Simulations indicated that one foot of ponding (constant head) on each of 14 consecutive days would result in 6 inches of recharge per day. The ponded area that also overlays the BA#1 uranium plume area was estimated to be approximately 24,000 square feet yielding a total recharge volume of 170,000 cubic feet (1.3 million gallons) over 14 days.

The HELP model was also used to evaluate ponding that resulted from river overtopping. Note, over the spring and summer of 2007, no observations indicate that the floodplain was entirely overtopped. Therefore, this scenario is conservative. River overtopping that would reach the BA#1 plume area was estimated to occur at an elevation of 940 feet, resulting in a ponding depth of 1 to 2 feet over the plume area. Based on data presented by Tortorelli (1999) the duration of a flooding event was evaluated to be 7 to 10 days. Recharge over the duration of river-generated ponding was calculated to be 6 inches per day; however, the area over which this might occur would include the entire northern lobe of the BA#1 uranium plume area (at elevations less than approximately 940 feet). This ponded area is estimated to be 39,100 square feet, yielding a recharge volume of 195,500 cubic feet (1.5 million gallons) over 10 days.

4.3.5 Sensitivity

It is acknowledged that there are input variables for which site-specific data are not completely known. To attempt to understand how changes in some of the variables may affect predicted recharge depths an informal sensitivity analysis was completed using the base case run wherein five years of actual precipitation were used.

The results indicated that the model's prediction of recharge was fairly sensitive to wilting point and evaporative zone depth producing recharge percents up to approximately 40% and down to approximately 4%. The model was relatively insensitive to many of the other parameter including leaf area index, soil thickness, curve number, and hydraulic conductivity.

4.4 HELP Model Results

The use of the HELP model provided a means to evaluate how rainfall is partitioned into evapotranspiration, runoff, storage, and recharge. The recharge component is particularly useful for evaluating the extent of mobilization of sorbed uranium from variably-saturated zone soils.

Model simulations indicate that, based on soil type, recharge ranges from 4.3 to 7.2 percent of annual average rainfall. These rates are consistent with what has been observed and reported by others (**Section 3.1**). Additional model simulations were run to evaluate the inches of recharge that would occur given a statistically based storm event. For instance, recharge was simulated to total 0.0155 inches over the 30 days following a 24-hour, 2-year storm event of 3.3 inches (Rea and Tortorelli, 1999). The 24-hour, 500-year storm event of 10 inches yielded a model estimate of 4.24 inches of total recharge over the 30 days following the storm event.

Modeling was also performed to estimate recharge from ponding scenarios. It was found that steady state ponding was reached quickly and in turn, steady state recharge rates were also established quickly. A relationship between steady state recharge and ponding was established. Based on this relationship, it was estimated that one foot of ponding with a two-week duration would result in approximately 6 inches per day recharge. This scenario is consistent with observations made during the spring and summer of 2007.

Based on transducer data collected at the most distant downgradient wells (TMW-24 and 02W48), changes in groundwater levels were shown to be unrelated to changes in river stage via alluvial soils, independent of river overtopping. If the focus of future work remains upgradient of TMW-24 and 02W48 as it has been to date, it is expected that the river will not impact groundwater conditions in the treatment area.

5.0 Summary and Conclusions

The conclusions of the hydrology assessment of recent and historical data are summarized as follows:

1) A total of 40.48 inches of rain fell between March 1and August 21, 2007. This total represents an almost 100% increase over typical rainfall during the same time period. Site precipitation data is consistent with data from the Oklahoma City weather station. The extreme precipitation and the consequent response in surface and groundwater were evaluated to draw conclusions regarding the site during transient hydrologic events.

2) The evaluation suggested that flows at the site would have to be around 45,000 cfs for bank overtopping to occur, which corresponds to a recurrence interval of between 4.5 and 5 years. Except for the mid-August 2007 hydrologic event, all the other events appear to have been driven by regional (frontal) precipitation events. With these events, there is a fairly uniform response in river levels and flow rates and in groundwater elevations. The mid-August 2007 event appears to have had a different rainfall pattern; river responses at Dover were far less than at Guthrie and groundwater responses in the upland sandstone wells were small relative to the other events. This information suggests that the sandstone wells are more influenced by regional groundwater boundary conditions as opposed to short-duration local precipitation events.

3) The water level data collected by transducer at 02W48 and TMW-24, 200 feet from the river, showed groundwater hydrographs that are strongly influenced by precipitation and are not influenced by river water levels, independent of river overtopping. In turn, it is expected that water quality at 02W48 and TMW-24 would be consistent with Sandstone C and Alluvial well waters, respectively, that is, uninfluenced by river water quality. It is expected that high river elevations alone will not impact groundwater elevations in the plume area as currently mapped (CSM Rev 01, ENSR 2006a).

4) In general, in the Sandstone B and Transition Zone soils, transient hydrologic events such as seen in the spring and summer of 2007 are not expected to result in changes to the groundwater gradients or the groundwater fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This suggests that groundwater elevations in Sandstone B and Transitions Zone soils are fairly stable. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events, however elevations generally responded uniformly indicating no net change in groundwater gradients and fluxes. The exception to this was that some data suggested periodic change in groundwater gradients between TMW-13 and 02W43. These changes lasted at most eight days; this short duration may result in short-term increases of flux, but relative to the total water balance, these increases are insignificant.

5) Throughout the spring and summer 2007 season, ponding was frequently observed in the BA#1 area. This ponding occurred and persisted because of the poorly-draining soils in that area that receive water from precipitation, upland runoff, and river water that inundated low-lying drainages.

6) All of the data collected over spring and summer of 2007 were from the BA#1 area. Though there is no data from the Western Alluvial Area, the following conclusions can be drawn:

   - Small site-scale differences in precipitation are not expected to have been significant.
   - Groundwater rises and falls are expected to be consistent with what was observed in the wells screened in alluvial soils in the BA#1 area. Groundwater rises and falls may be as much as 5 to 10 feet, but the rises and falls occur concurrently so there is no change in gradient. Short-term changes in flux are small relative to the total water budget for the site.

- In the BA#1 area, rises and falls in the river did not impact groundwater elevations or water quality 200 feet from the river. Groundwater impacts from uranium in the Western Alluvial area occur at a much greater distance than 200 feet from the river. Therefore, the rises and falls in the river are not expected to impact the WAA where uranium occurs.
- The mechanisms that cause ponding in the Western Alluvial are the same as for the other floodplain areas of the site. Site observations indicate that there is a low-lying drainage feature that runs next to Route 74 that may serve as a conduit of river water to the southern area of the escarpment when river water levels are high.

The HELP model was used with precipitation and soil characteristics to estimate a depth of recharge based on a variety of soil characteristics and depths of rainfall. Factors that control recharge to the water table are the intensity, frequency, and duration of rainfall as well as soil properties. Results of the HELP model can be summarized as follows:

- Average annual recharge rates, regardless of soil type, were fairly consistent with one another (4.3 to 7.2%) and are consistent with what is reported in the literature. A sensitivity evaluation indicates that the model is not that sensitive to soil thickness and therefore, to depth to water.
- For an extreme statistical rainfall event, 7-day, 500-year rainfall (total precipitation of 15.5 inches), recharge was simulated to be almost 8 inches of recharge over 30 days. Over the BA#1 plume area this amounts to 48,200 cubic feet or 361,000 gallons over 30 days.
- The HELP model was used to simulate ponding and consequent recharge that occurred from extreme precipitation and accumulated runoff. The simulations relied on observations made during spring and summer 2007. Ponding of 1 to 2 feet lasting approximately 14 days was estimated to result in a recharge volume over the BA#1 plume area of 170,000 cubic feet or 1.3 million gallons over 14 days.
- The HELP model was used to simulate ponding and consequent recharge that occurred from river bank overtopping that would reach elevation 940 feet, thus causing 1 to 2 feet of ponding in the BA#1 plume area. Statistical studies indicated a flooding event of this magnitude may last for 7 to 10 days. Model output estimated a recharge volume of 195,500 cubic feet or 1.5 million gallons over 10 days.

HELP modeling was conducted not necessarily to provide a precise estimate of recharge for any of the given scenarios discussed above, but rather to provide bounds on data heretofore uncharacterized. This study has helped to better conceptually characterize the site especially in terms of transient hydrologic processes.

6.0 References

Adams, G.P, and D.L. Bergman, 1995. Geohydrology of Alluvium and Terrace Deposits, Cimarron River from Freedom to Guthrie, Oklahoma. USGS WRI 95-4066.

ARCADIS. 2006. Work Plan for In-situ Bioremediation of Groundwater. Cimarron Facility. Crescent, OK.

ARCADIS. 2008. Site Decommissioning Plan – Groundwater Decommissioning Amendment

Belden, Mark. 2000. Hydrogeologic Report of the El Reno, Fairview, Isabella, and Loyal Minor Groundwater Basins in Central Oklahoma. Oklahoma Water Resources Board (OKWRB) Technical Report 2001-1

ENSR. 2006a. Conceptual Site Model Rev 01.

ENSR. 2006b. Groundwater Modeling Report.

Flynn, K.M., Kirby, W., and Hummel, P.R., 2005, User's manual for program PeakFQ, annual flood frequency analysis using Bulletin 17B guidelines: U.S. Geological Survey Techniques and Methods Report 05-xxxx [Draft: PDF | chm]

Geraghty, James J., David W. Miller, Frits vander Leeden, Fred L.Troise. 1973. Water Atlas of the United States. A Water Information Center Publication – Port Washington. N.Y. 11050

Interagency Advisory Committee on Water Data (IACWD). 1982. Guidelines for determining flood-flow frequency: Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston,Va., 183 p., http://water.usgs.gov/osw/bulletin17b/bulletin_17B.html

National Weather Service. 2007. http://www.srh.noaa.gov/oun/hydro/fpoints/fpindex.php?fpid=dovo2 and http://www.srh.noaa.gov/oun/hydro/fpoints/fpindex.php?fpid=gtro2.

Natural Resources Conservation Service. 2007. http://websoilsurvey.nrcs.usda.gov/app/

Oklahoma Climatological Survey. http://climate.ocs.ou.edu/county_climate/Products/CountyPages/logan.html.

Oklahoma Water Resources Board (OWRB). 2007. Hydrologic Drought of Water Year 2006: A Historical Context. Published by the Oklahoma Water Resources Board in cooperation with the U.S. Geological Survey and the Oklahoma Climatological Survey

Rea, Alan and Robert L. Tortorelli. 1999. Digital Data Sets of Depth-Duration-Frequency of Precipitation for Oklahoma. U.S. Geological Survey Open File Report 99-463.

Reed, E.W., Mogg, J.L., Barclay, J.E., and Peden, G.H., 1952, Ground-water resources of the terrace deposits along the northeast side of the Cimarron River in Alfalfa, Garfield, Kingfisher, and Major Counties Oklahoma: Oklahoma Water Resources Board Bulletin 9, 101 p.

Schroeder, P.R., T.S. Dozier, P.A., Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton. 1994. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3." EPA/600/R-94/168a and b. U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Sims, P.L., J.A. Bradford. 2003. Evapotranspiration in Southern Plains Mixed-Grass Prairies. International Rangeland Congress. pp. 1094-1096. http://ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=146593

Stephen J. Stadler and Stephen J. Walsh. 1983. Development of a Model for Evapotranspiration Estimates Using Satellite Data. Oklahoma State University Environmental Institute Publications and Reports. E-019.

Tortorelli, Robert L. 1999. Statistical Summaries of Streamflow in Oklahoma through 1999. Water-Resources Investigations Report 02-4025.

Tortorelli, Robert L. and McCabe, L.P., 2001, Flood frequency estimates and documented and potential extreme peak discharges in Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 01-4152, 59 p.

United States Geological Survey (USGS). 2007a. National Water Information System: Web Interface.

Guthrie: http://waterdata.usgs.gov/nwis/inventory/?site_no=07159100&

Dover: http://waterdata.usgs.gov/nwis/inventory/?site_no=07160000&

Crescent: http://waterdata.usgs.gov/nwis/dv?referred_module=sw&site_no=07159400

United States Geological Survey (USGS). 2007b. StreamStats. http://streamstats.usgs.gov/gages/viewer.htm

TABLES

Table 3-1
Hydrology Addendum
Summary of PKFQWin Results for Flow (cfs)

Exceedance Probability (1/year)	Calculated Dover flow (cfs) (1)	Calculated Guthrie flow (cfs) [1]	Estimated flow (cfs) at Rte 74 [2]	Recurrance Interval Flood (year)
0.995	3,468	2,462	2,714	1.005
0.99	4,160	3,248	3,476	1.010
0.95	6,870	6,651	6,706	1.053
0.9	9,002	9,512	9,385	1.111
0.8	12,520	14,350	13,893	1.25
0.6667	17,080	20,620	19,735	1.5
0.5	23,730	29,520	28,073	2
0.4292	27,200	34,020	32,315	2.3
0.2	45,440	55,870	53,263	5
0.1	64,090	75,550	72,685	10
0.04	92,780	101,800	99,545	25
0.02	118,000	122,000	121,000	50
0.01	146,800	142,400	143,500	100
0.005	179,300	162,900	167,000	200
0.002	228,800	190,300	199,925	500

Notes
1 - Based on PKFQWin.
2 - Based on linear interpolation with distance.

Table 3-2
Hydrology Addendum
Summary of PKFQWin Results for Depth (feet)

Exceedance Probability (1/year)	Calculated Dover stage (ft) [1]	Calculated Dover depth (ft) [2]	Calculated Guthrie stage (ft) [1]	Calculated Guthrie depth (ft) [2]	Estimated depth (ft) at Route 74 [3]	Estimated elevation (ft) at Route 74 [4]	Estimated Flow (cfs)	Recurrance Interval Flood (year)
0.995	13.6	3.9	4.4	3.5	3.6	928.6	2,714	1.005
0.99	14.0	4.3	4.8	4.1	4.1	929.1	3,476	1.010
0.95	15.1	5.2	6.2	6.1	5.9	930.9	6,706	1.053
0.9	15.8	5.8	7.0	7.2	6.9	931.9	9,385	1.111
0.8	16.7	6.6	8.1	8.8	8.3	933.3	13,893	1.25
0.6667	17.6	7.4	9.2	10.4	9.6	934.6	19,735	1.5
0.5	18.6	8.2	10.5	12.2	11.2	936.2	28,073	2
0.4292	19.1	8.7	11.1	13.1	12.0	937.0	32,315	2.3
0.2	20.9	10.2	13.5	16.5	15.0	940.0	53,263	5
0.1	22.3	11.4	15.2	19.0	17.1	942.1	72,685	10
0.04	23.9	12.8	17.2	21.8	19.6	944.6	99,545	25
0.02	25.1	13.9	18.6	23.8	21.4	946.4	121,000	50
0.01	26.1	14.7	19.9	25.7	23.0	948.0	143,500	100
0.005	27.2	15.7	21.1	27.4	24.5	949.5	167,000	200
0.002	28.6	16.9	22.6	29.6	26.4	951.4	199,925	500

Notes:
1 - Based on PKFQWin.
2 - Based on stage-depth relationship, assumes rectangular channel.
3 - Based on linear interpolation with distance.
4 - Bottom Elevation of Cimarron River at Rte 74 Estimated at 925 feet.

Table 4-1
Hydrology Addendum
HELP Model Inputs/Outputs for
Base Case Runs

BASE CASE 1 - 5 Year Simulation Using Synthetic Rainfall

INPUTS		
Weather Data		
Evapotranspiration Data		Source
City:	OKC	
State:	OK	
Latitude:	35.88	Adjusted for site
Evaporative Zone Depth:	25 inches	Based on guidance document
Maximum Leaf Area Index:	4.5	4.5 recommended by guidance document.
Growing Season Start Day:	86	Default based on location
Growing Season End Day:	310	Default based on location
Average Wind Speed:	12.5 MPH	Default based on location
First Quarter Relative Humidity:	64 %	Default based on location
Second Quarter Relative Humidity:	66 %	Default based on location
Third Quarter Relative Humidity:	63 %	Default based on location
Fourth Quarter Relative Humidity:	66 %	Default based on location
Precipitation Data		
5 year synthetic	30.89 in/year	Using default monthly means.
OR		
Actual data from 2003-2007		Using actual measurements from OKC
Temperature Data		
5 year synthetic		Using default monthly means.
Solar Radiation Data		
5 year synthetic	35.88 degrees	Latitude to generate data.
Soil and Design Data		
General Information		
Area:	1 Acre	Assume a unit area of 1 acre in BA#1 flood plain
Percent of area were runoff is possible:	100 %	None is water
Specify initial soil moisture:	No	Over long simulations, soil moisture will come to steady state regardless of initial inputs.
Soil Layer Information:		
Soil Layer 1 - Layer Type	1	Type 1 address vertical percolation
Soil Layer 1 - Layer Thickness	52.08 inches	Thickness of flood plain silty-clay based on data from TMW-23, 02W48, 02W46, TMW-09
Soil Layer 1 - Soil Texture	12	Silty-clay soil type
Soil Layer 1 - Total Porosity	0.471 vol/vol	Default values for soil type 12
Soil Layer 1 - Field Capacity	0.342 vol/vol	Default values for soil type 12
Soil Layer 1 - Wilting Point	0.21 vol/vol	Default values for soil type 12
Soil Layer 1 - Saturated Hydraulic Conductivity	1.20E-03 cm/sec	Based on slug test data in wells with silty clay (see Table 1, GW Modeling Report)
Soil Layer 2 - Layer Type	1	Type 1 address vertical percolation
Soil Layer 2 - Layer Thickness	50 inches	Thickness of flood plain sands based on data from TMW-23, 02W48, 02W46, TMW-09
Soil Layer 2 - Soil Texture	2	Sand soil type
Soil Layer 2 - Total Porosity	0.437 vol/vol	Default values for soil type 12
Soil Layer 2 - Field Capacity	0.062 vol/vol	Default values for soil type 12
Soil Layer 2 - Wilting Point	0.024 vol/vol	Default values for soil type 12
Soil Layer 2 - Saturated Hydraulic Conductivity	4.80E-02 cm/sec	Based on slug test data in wells with sand (see Table 1, GW Modeling Report)
Runoff Curve Number Information		
User Specified Runoff Curve Number	50	Based on soil type 2 and fair grass condition

Table 4-1
Hydrology Addendum
HELP Model Inputs/Outputs for
Base Case Runs

BASE CASE 1 - 5 Year Simulation Using Synthetic Rainfall				
OUTPUT				
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	27.85	5	100	
Runoff	0.04	0.0439	0.07	
Evapotranspiration	26.603	4.3104	95.53	
Percolation/Leakage Through Layer 2	1.07	0.96	3.84	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	0.154	1.46	0.55	
BASE CASE 2 - 5 Year Simulation Using Actual Rainfall from 2002-2006				
INPUTS				
Same as above except rainfall inputs				
OUTPUT				
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	27.47	6.232	100	
Runoff	0	0	0	
Evapotranspiration	25.44	4.03	92.99	
Percolation/Leakage Through Layer 2	1.98	0.91	7.2	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.053	3.13	-0.195	
BASE CASE 3 - 6 Year Simulation Using Actual Rainfall from 2002-2006 and partial 2007				
INPUTS				
Same as above except rainfall inputs				
OUTPUT				
2007	Total	Std. Dev.	Percent (%)	
Precipitation	43.92		100	
Runoff	0.14		0.32	
Evapotranspiration	32.63		74.31	
Percolation/Leakage Through Layer 2	12.08		27.5	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.936		-2.13	
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	30.21	8.728	100	
Runoff	0.023	0.0572	0.077	
Evapotranspiration	26.695	4.58	88.361	
Percolation/Leakage Through Layer 2	3.71	4.19	12.29	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.22	2.92	-0.729	

Table 4-2
Hydrology Addendum
Summary of HELP Model Simulation Results

Variability in recharge rates based on Soil Type using 2002-2006 rainfall data. See Section 4.3.2

	Average Annual Recharge inches	Average Annual Recharge percent	
1 - Floodplain with overlying silty-clay, Base Case	1.89	6.9	
2 - Silty-clayey-sand with no underlying sand	1.42	5.2	As seen at transition wells, among other locations
3 - Fill underlain by sandstone	1.21	4.4	As seen at TMW-21, TMW-08

Variability in recharge rates based on alluvial soils and different recurrence interval precipitation events. See Section 4.3.3

		Precipitation on July 1st or July 1st to 7th (inches)[1]	Recharge totaled over 30 days after extreme rainfall event (inches)
a	24-hour duration, 2 year-recurrence interval	3.3	0.41
b	24-hour duration, 100 year-recurrence interval	9.5	5.49
c	24-hour duration, 500 year-recurrence interval	10	5.94
d	7-day duration, 2 year-recurrence interval	4.9	0.013
e	7-day duration, 100 year-recurrence interval	12.4	6.24
f	7-day duration, 500 year-recurrence interval	15.5	9.67

1 - From Rea and Tortorelli, 1999

Table 4-3
Hydrology Addendum
Duration of Statistical High Flows

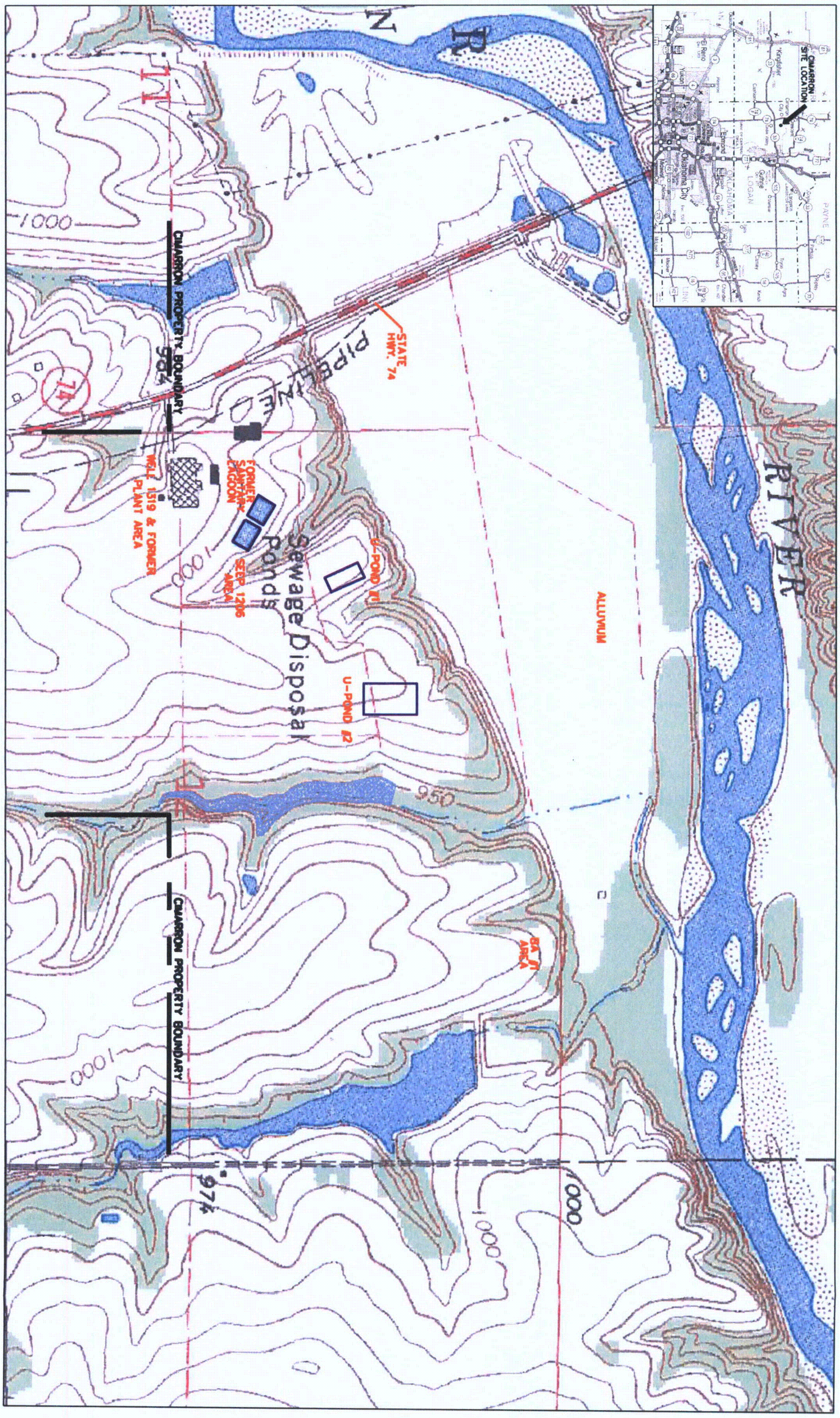
DOVER - Magnitude and probability of annual high flow based on period of record 1974-1999. Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent						
Period (consecutive days)	**2 years 50%**	**5 years 20%**	**10 years 10%**	**25 years 4%**	**50 years 2%**	**100 years 1%**
1	18,400	34,700	49,100	72,100	93,000	117,000
3	12,800	23,900	33,500	48,700	62,300	78,000
7	7,520	13,900	19,500	28,400	36,500	45,800
10	6,240	11,500	15,900	22,800	28,900	35,800
30	3,390	5,900	7,790	10,400	12,500	14,600
60	2,330	3,890	5,020	6,540	7,720	8,930

GUTHRIE - Magnitude and probability of annual high flow based on period of record 1974-1999. Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent						
Period (consecutive days)	**2 years 50%**	**5 years 20%**	**10 years 10%**	**25 years 4%**	**50 years 2%**	**100 years 1%**
1	24,400	46,600	62,600	83,500	99,000	114,000
3	16,400	32,100	44,300	61,300	74,800	88,800
7	9,660	19,600	27,900	40,200	50,600	61,900
10	7,510	15,500	22,300	32,700	41,800	51,900
30	3,750	7,460	10,600	15,400	19,600	24,300
60	2,570	5,110	7,280	10,600	13,400	16,500

CIMARRON SITE AT RTE 74 - Magnitude and probability of annual high flow based on period of record 1974-1999. Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent						
Period (consecutive days)	**2 years 50%**	**5 years 20%**	**10 years 10%**	**25 years 4%**	**50 years 2%**	**100 years 1%**
1	22,900	43,625	59,225	80,650	97,500	114,750
3	15,500	30,050	41,600	58,150	71,675	86,100
7	9,125	18,175	25,800	37,250	47,075	57,875
10	7,193	14,500	20,700	30,225	38,575	47,875
30	3,660	7,070	9,898	14,150	17,825	21,875
60	2,510	4,805	6,715	9,585	11,980	14,608

FIGURES

DWG. NO. 040200056



REFERENCE: UNITED STATES GEOLOGICAL SURVEY
CRESCENT QUADRANGLE, OKLAHOMA-LOGAN CO.
7.5 MINUTE SERIES (TOPOGRAPHIC), 1970 (PHOTOINSPECTED 1981).

SCALE IN FEET: 0 800 1600

SHEET NUMBER:	FIGURE NUMBER:
1	2-1

FIGURE 2-1
SITE LOCATION MAP
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

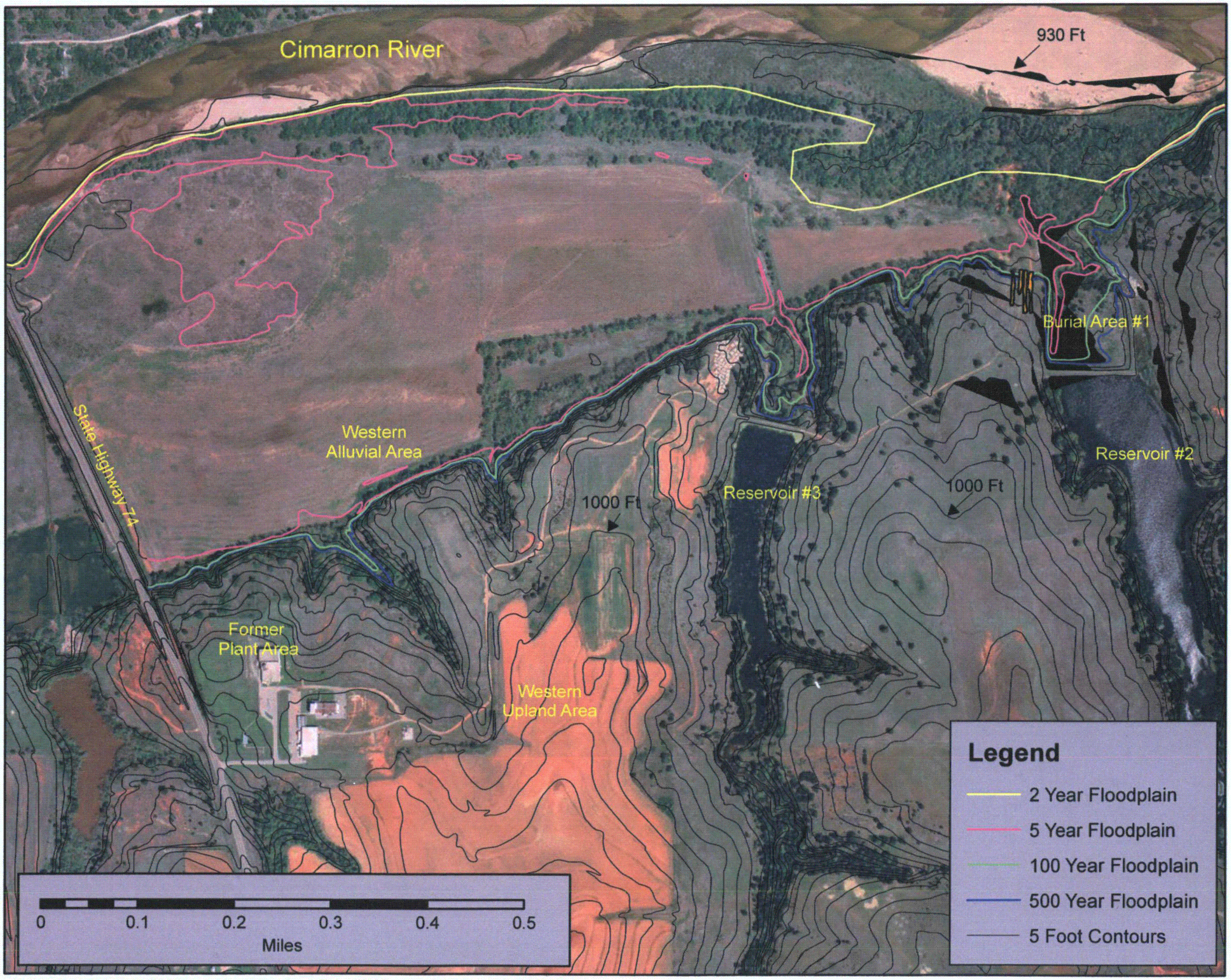
SCALE:	DATE:	PROJECT NUMBER:
1" = 800'	9/22/06	04020-044-327

ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

DESIGNED BY:	
DRAWN BY:	JAS
CHECKED BY:	DJF
APPROVED BY:	DJF

REVISIONS			
NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS
3.		6/8/05	JAS



J:\Water\ProjectFiles\P40\4020\044-Cimarron\Addendum-WP\data\GIS\flood map\Flood_Map_April 2008.mxd

ENSR | AECOM

Floodplain Map showing 2-year, 5-year 100-year, and 500-year flood elevations

Scale	Date	Project Number
1:8186	April 2008	04020-044-400

Drawn By: AH

Figure Number: 3-1

Sheet Number: 1

Figure 3-2
Hydrology Addendum
Precipitation measured
March 1, 2007 to August 21, 2007

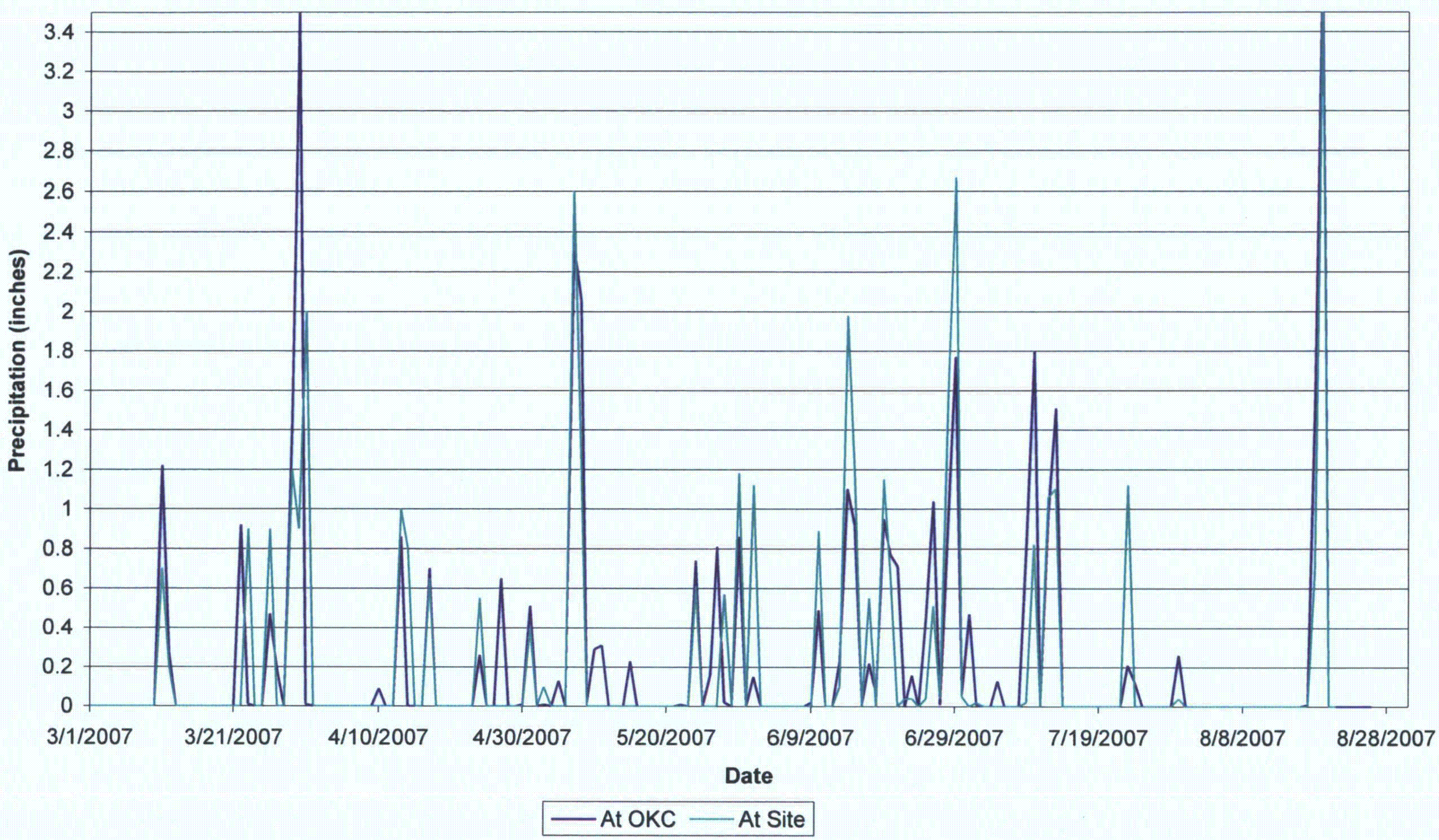


Figure 3-3
Hydrology Addendum
Flows on the Cimarron River between March 1, 2007 and August 21, 2007
at Dover

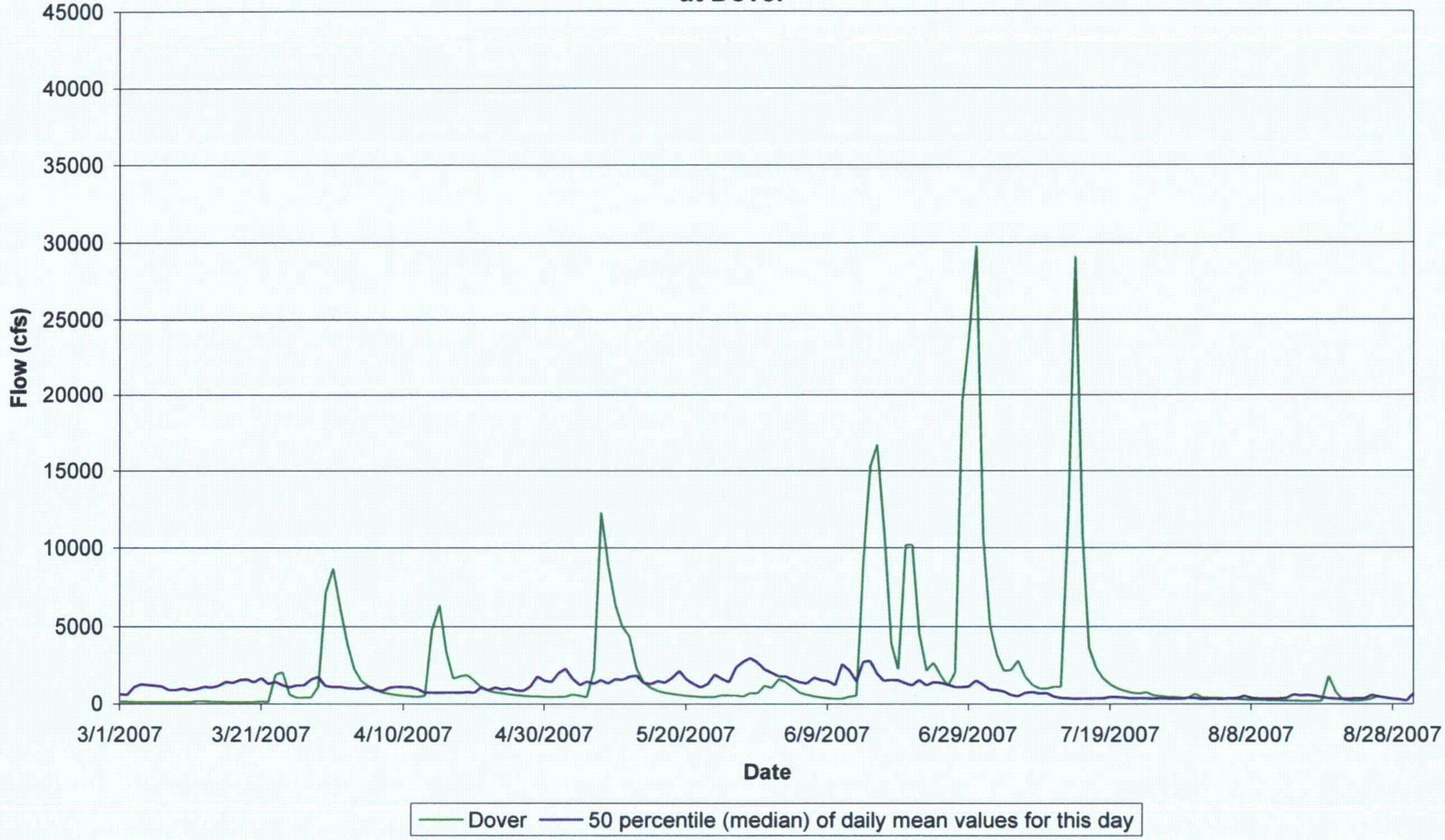


Figure 3-4
Hydrology Addendum
Flows on the Cimarron River between March 1, 2007 and August 21, 2007 at Guthrie

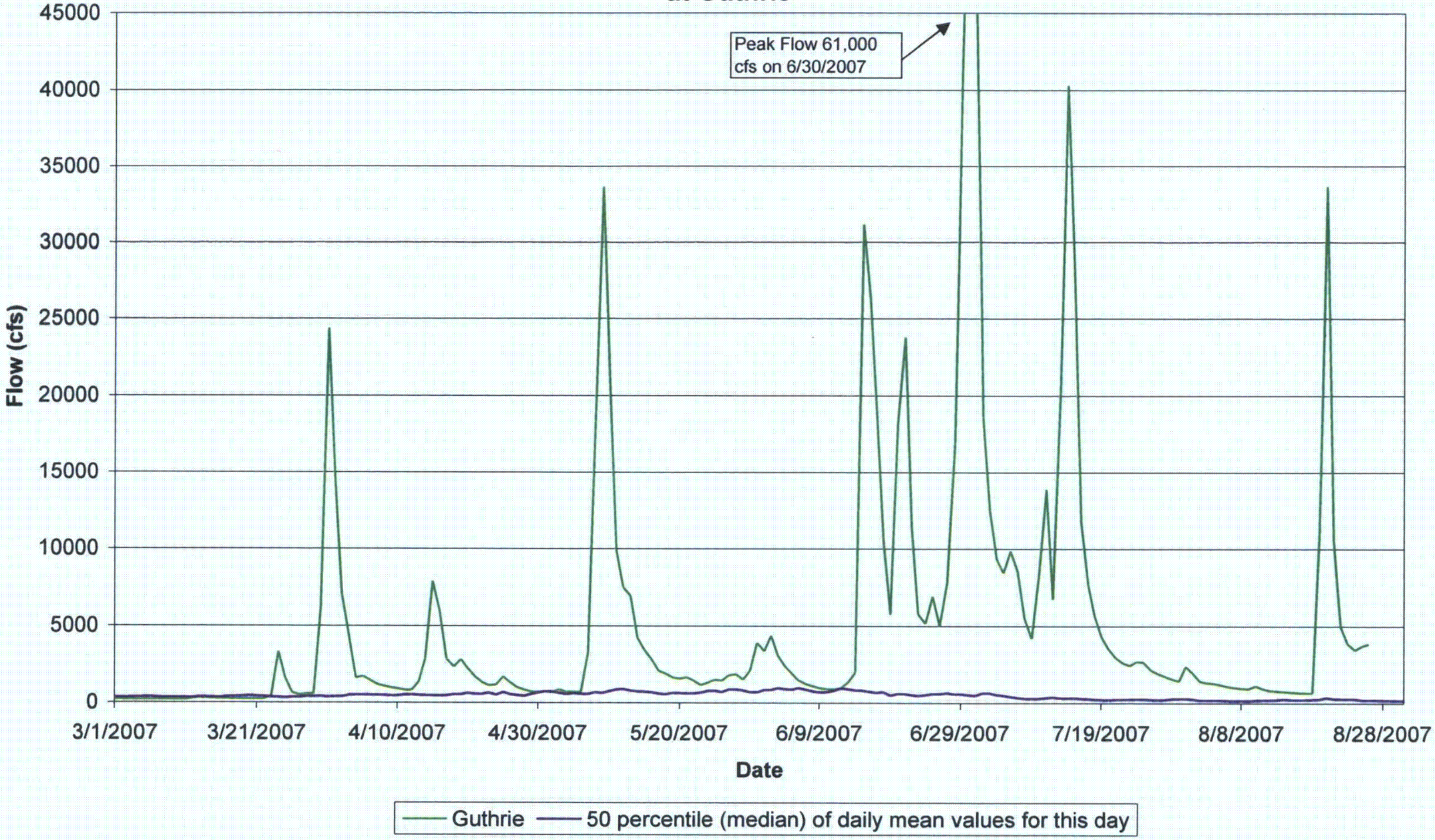
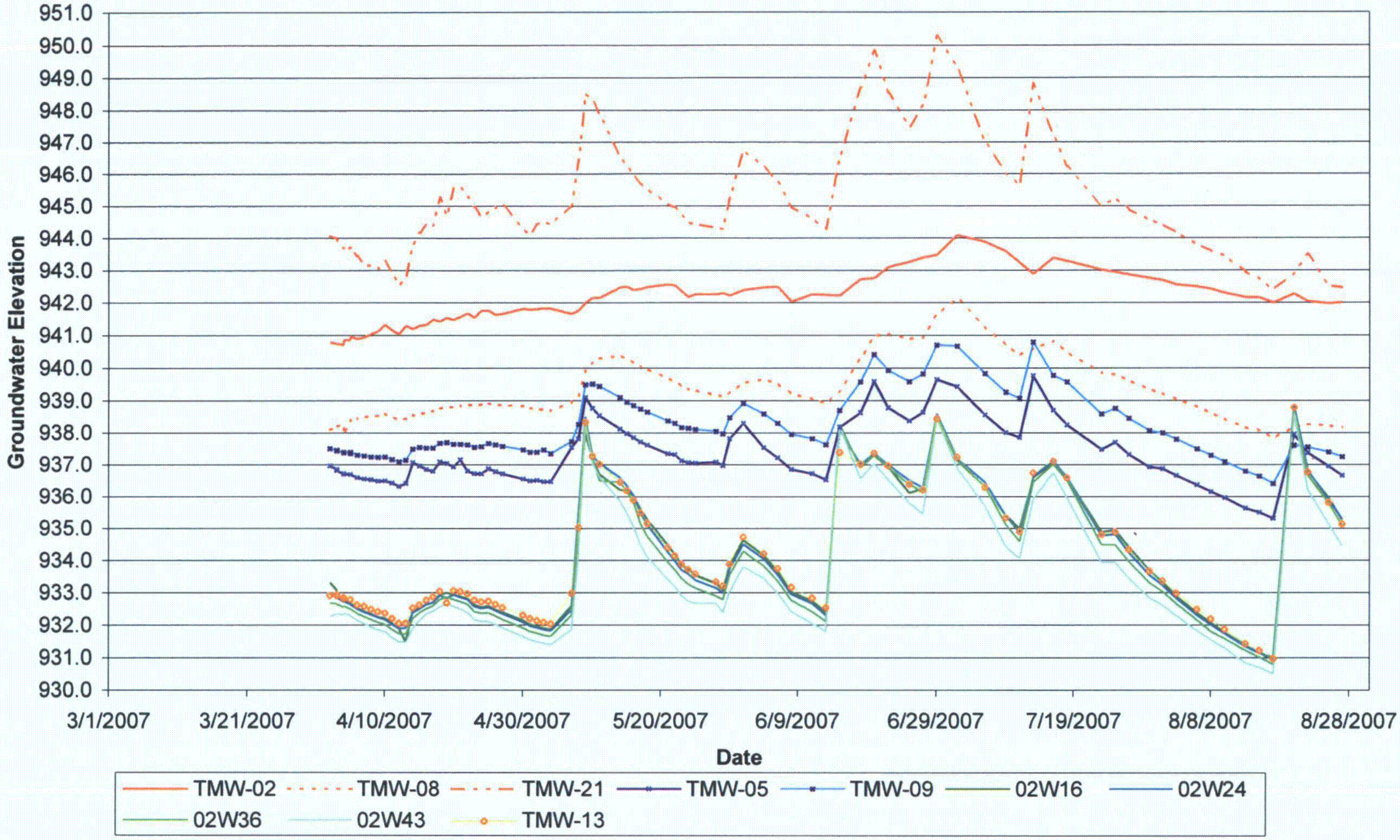
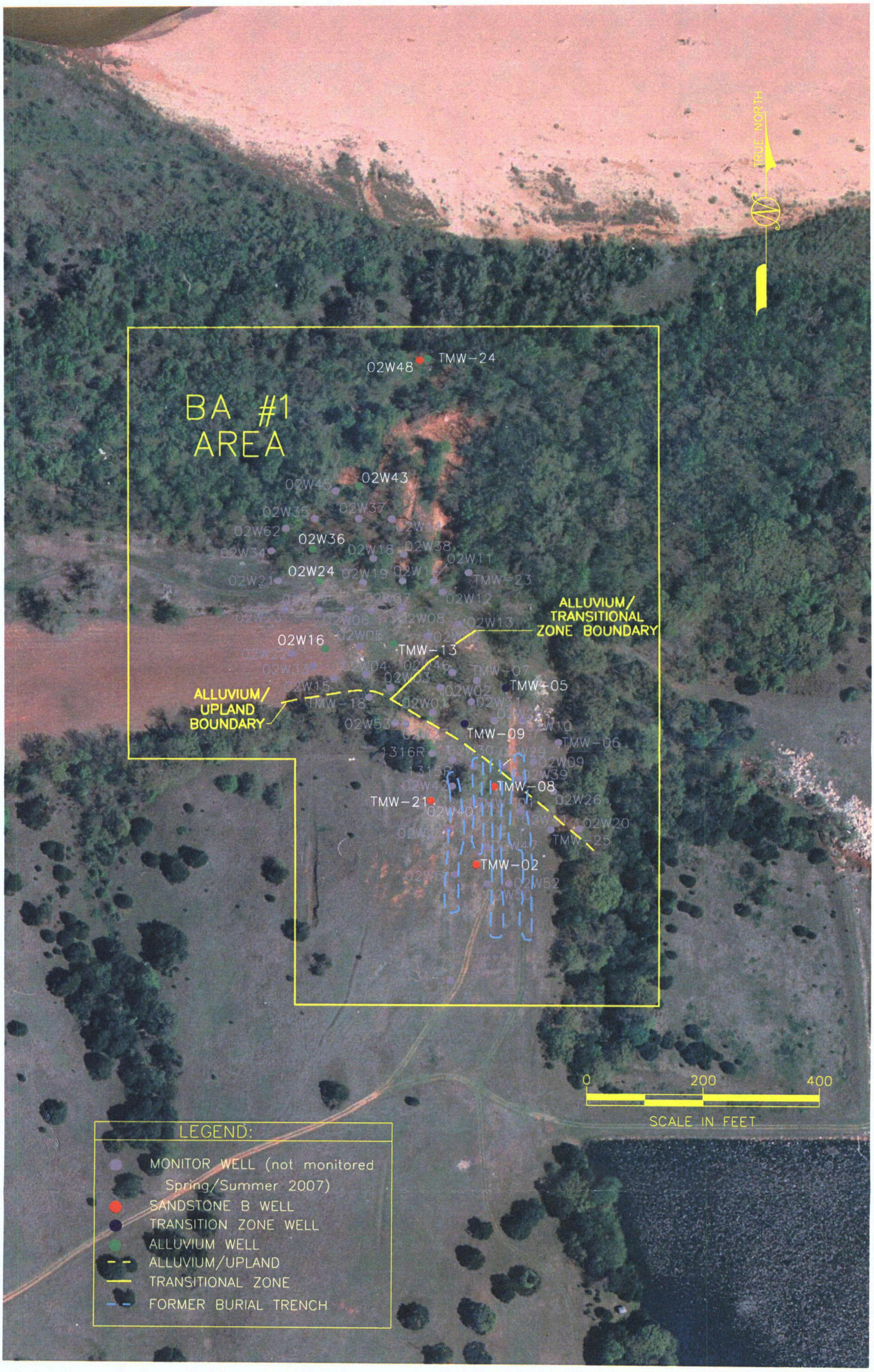


Figure 3-5
Hydrology Addendum
Groundwater Elevations at BA#1 Wells April 1, 2007 and August 20, 2007





SHEET NUMBER: 1

FIGURE NUMBER: 3-6

FIGURE 3-6
BA #1
LOCATION OF WELLS MONITORED FOR
GROUNDWATER ELEVATION APR.-AUG. 2007
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1"= 200'	10-31-07	04020-044-400

ENSR
INTERNATIONAL
4888 LOOP CENTRAL DR. SUITE 600
HOUSTON, TEXAS 77081
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.COM

DESIGNED BY:	REVISIONS			
	NO.:	DESCRIPTION:	DATE:	BY:
DRAWN BY:	1		4/01/05	JAS
JAS	2		6/17/05	
CHECKED BY:				
DJF				
APPROVED BY:				
DJF				

Figure 3-7
Hydrology Addendum
Water level data as measured at the transducers in TMW-24 and 02W48 and site rainfall
March 1, 2007 to August 21, 2007

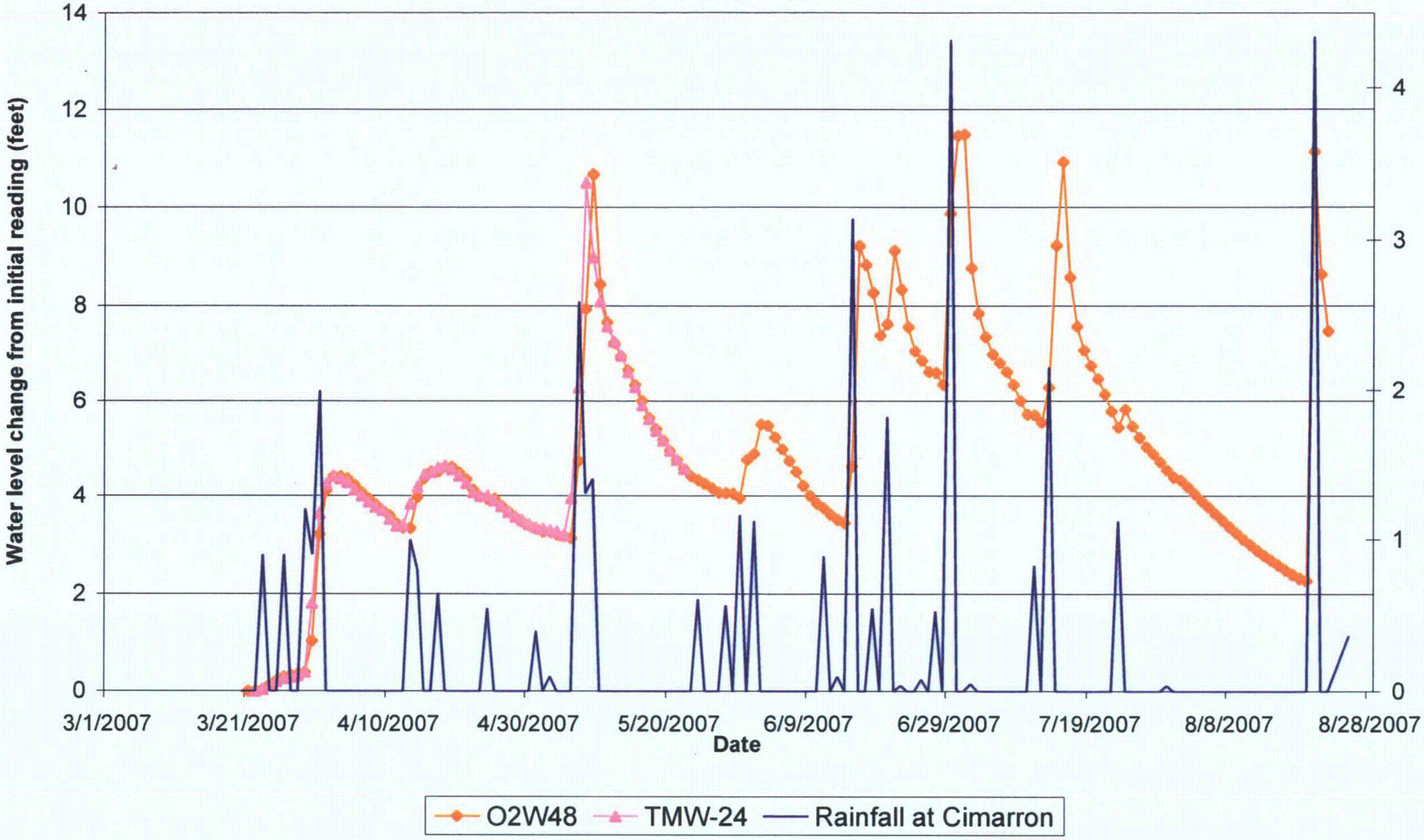
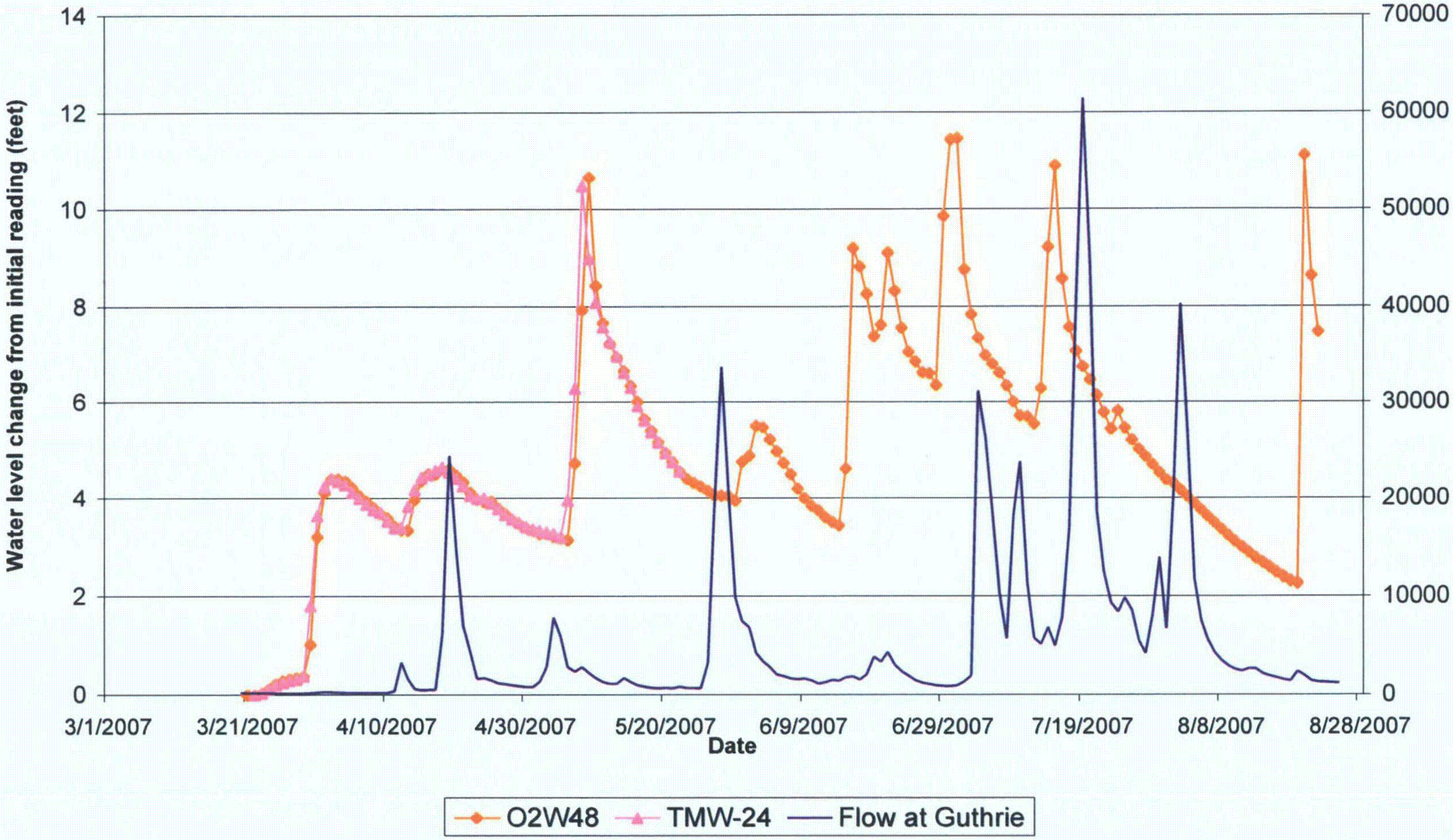
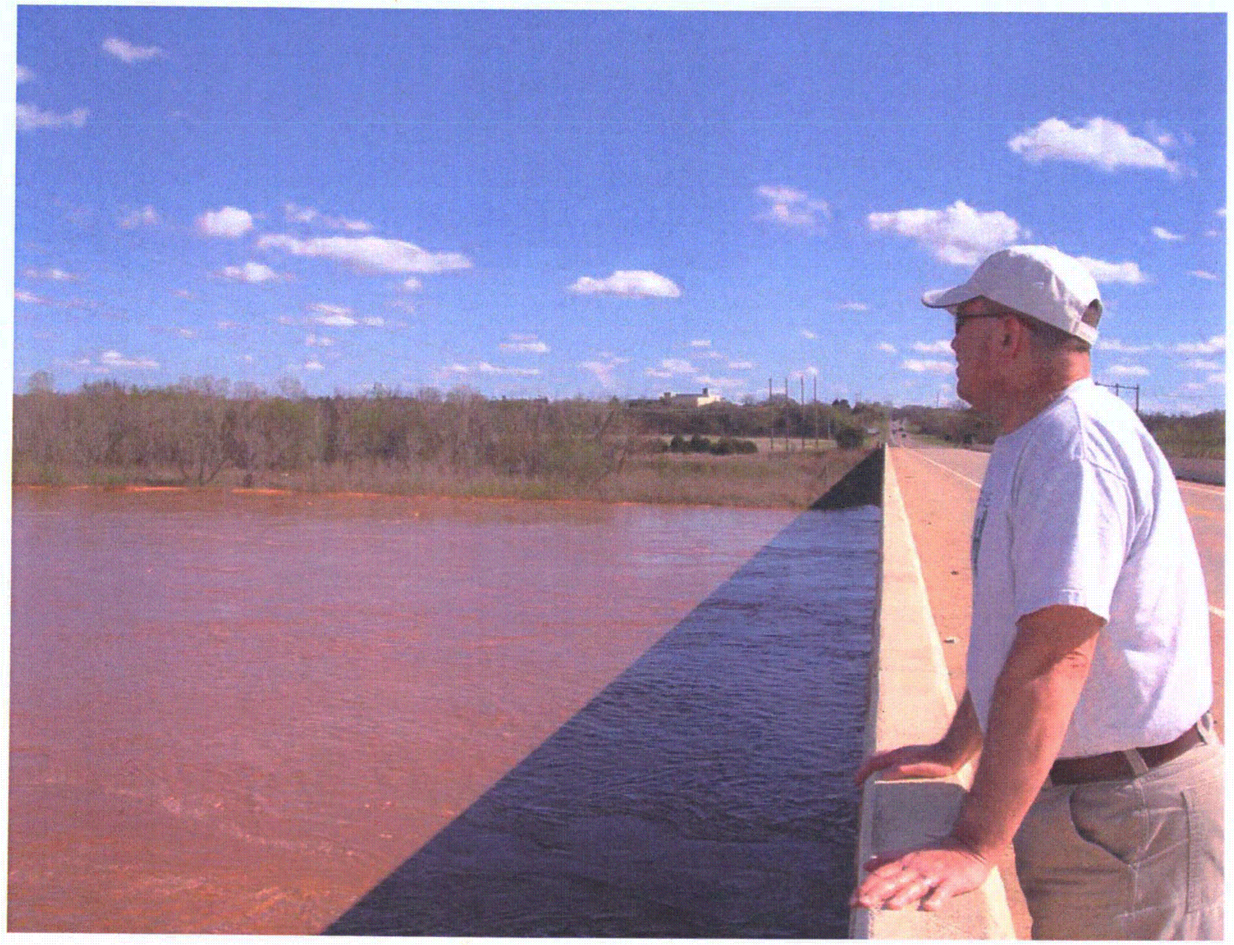


Figure 3-8
Hydrology Addendum
Water level data as measured at the transducers in TMW-24 and 02W48
and Guthrie flow data
March 1, 2007 to August 21, 2007





April 2, 2007

October 18, 2007

Cimarron River at Route 74 Looking South

April 2008 Job No. 04020-044-400

Figure 3-9

www.ensr.aecom.com

April 2, 2007

October 18, 2007

BA#1 Floodplain Area

April 2008 Job No. 04020-044-400

Figure 3-10

www.ensr.aecom.com

May 15, 2007

October 18, 2007

Cimarron River at Route 74 Looking South

April 2008 Job No. 04020-044-400

Figure 3-11

www.ensr.aecom.com

May 15, 2007

October 18, 2007

BA#1 Floodplain Area	Figure 3-12
April 2008 Job No. 04020-044-400	www.ensr.aecom.com

July 26, 2007

October 18, 2007

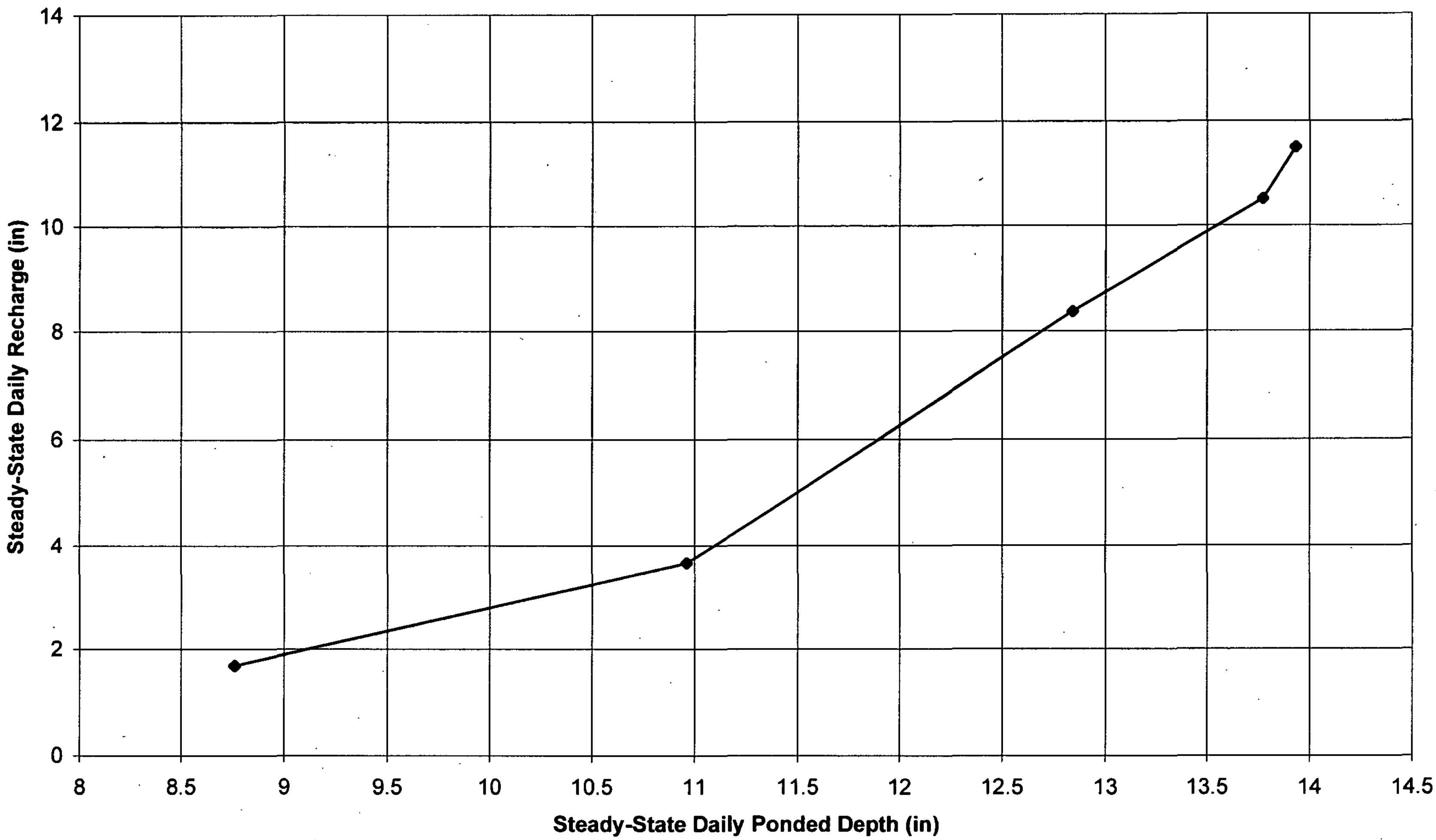
Cimarron River at Route 74 Looking South	Figure 3-13
April 2008 Job No. 04020-044-400	www.ensr.aecom.com

July 26, 2007

October 18, 2007

Western Alluvial Area	Figure 3-14
April 2008 Job No. 04020-044-400	www.ensr.aecom.com

Figure 4-1
Hydrology Addendum
Simulated Daily Ponded Depth versus Simulated Daily Recharge



Appendix C

Data Quality Objectives

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
1: Development of Groundwater Decommissioning Plan and Approval (by the NRC and ODEQ)	A. Evaluate uranium precipitation and immobilization; evaluate the mass of iron sulfide required for remediation system	1) Collect groundwater and soil geochemical data	ARCADIS sampling procedures	Water level data to ±1 foot, sample according to low-flow methods
		2) Update thermodynamic database 3) Perform model runs 4) Analyze output	Defined in peer-reviewed literature	Verification and validation for off-the-shelf (commercial) software is not required.
2: Baseline Sampling and Initial Treatment System Installation	A. Determination of the baseline iron mineralogy, including iron sulfide	1) Soil sampling	ARCADIS sampling procedures and anoxic sampling guidance provided by EPA (Wilkin, 2006). Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.	Sample to prevent air oxidation using gloved bag for handling samples at surface; seal samples to protect from oxidation and ship on dry ice for analysis.
		2) Soil digestions and analysis	EPA Protocol 3050B and 3052	Not applicable
		3) Selective extraction	ARCADIS Procedures, procedures published in the peer-reviewed literature	Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.
		4) Acid-volatile sulfide measurement	EPA Draft Protocol 821R91100	Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.
		5) X-ray diffraction	Defined in peer-reviewed literature	Not quantitative (detection only)
		6) SEM/EDS	Defined in peer-reviewed literature	Not quantitative (detection only)
		7) XAS	Defined in peer-reviewed literature	Not quantitative (detection only)
	B. Additional field characterization, including groundwater	Field parameters: 1) pH	ARCADIS procedures	± 0.2 standard units

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
		2) Ferrous Iron	ARCADIS procedures	± 10%
		3) DO		± 10%
		4) Conductivity		± 10%
		5) Temperature		± 10%
		Analytical laboratory	EPA Protocols	
		6) Total Organic Carbon	EPA 415.1	RL = 0.2 mg/L
		7) Anions (nitrate, nitrite, sulfate)	EPA 300.0	RL = 0.1 mg/L
		8) Total dissolved solids	EPA 160.1	RL = 0.1 mg/L
		9) Total and dissolved iron	EPA 200.8	RL = 0.025 mg/L
		10) Sulfide	EPA 376.1	RL = 0.1 mg/L
		11) Alkalinity	EPA 310.1	RL = 5 mg/L
		12) Isotopic uranium and total activity	LNST & DOE EML procedures	LNST Minimum Detectable Activities: 18 pCi/L total U, total alpha, total beta 9 pCi/L U-234 and U-238 5 pCi/L U-235 LNST precision: 6 pCi/L at 1 σ or 6% at 1 σ, whichever is greater

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
		13) Total uranium (mass concentration)	EPA Protocol 6020	RL = 0.001 mg/L
	C. Install initial treatment system including remediation wells and performance monitoring wells.	1) Well/boring location selection and determination		± 2 ft from bottom of well screen
		2) Boring lithologic logging		Standard USCS
		3) IDW Management		Collection of saturated soils and radiological characterization
		4) Well construction		Screened at top of impacted interval
		5) Survey of wells		Industry standard (± 2 ft laterally and ± 0.1 ft vertically)
		6) Water level gauging	ARCADIS procedures	± 1 ft
		7) Extraction Pump Installation		± 10% of proposed spacing
		8) Hydraulic evaluation of sustainable injection and extraction yields		Defined in procedure
		9) Injection tracer test		Defined in procedure
		10) Determination of mobile porosity		Defined in procedure
		11) Determination of groundwater velocity		Defined in procedure

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
	D. Operate initial treatment system.	1) Carbon substrate delivery	ARCADIS procedures	± 20% of proposed amendment dose
		2) Amendment (iron sulfate) delivery		± 20% of proposed TOC dose
		3) Adjust flow rates and frequency of injection		Defined in procedure
	E. Collect system performance data for groundwater and soil iron mineralogy data	Same as Task 1A, 2A, and 2B	Same as Task 1A, 2A, and 2B	Same as Task 1A, 2A, and 2B
	F. Laboratory column testing	1) Measurement of uranium level in column effluent 2) Measurement of soil mineralogy in columns for testing	ARCADIS procedures (Appendix G)/ Guidance provided in Thornton et al 2007	Defined in procedure; uranium analysis as in Task 2B and soil analyses as in Task 2A
	G. Update/adjust Geochemical Model	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4
3: Full-scale Systems Operation/Active Treatment	A. Expand treatment systems to complete functionality	Same as Tasks 1A, and 2A-F	Same as Tasks 1A, and 2A-F	Same as Tasks 1A, and 2A-F
	B. Continue to operate and optimize systems	1) Perform semi-annual (seasonal) groundwater monitoring	Same as Task 2B	Same as Task 2B
		2) Soils mineralogy demonstration testing	Same as Task 2A	Establishment of at least 1 part uranium to 80 parts iron (by mass).
	C. Update/adjust Geochemical Model	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
4: Remedy Completion Demonstration and License Termination	A. Collection of groundwater uranium concentrations and statistical trend analysis	1) Groundwater sampling and analysis	Same as Tasks 2B, 12 and 13	Same as Tasks 2B, 12 and 13
		2) Statistical analysis of trends over 8 quarters	EPA Guidance and Mann-Kendall Test/Sen's Slope Estimator; ARCADIS procedure will be prepared for this assessment	To be described in ARCADIS procedure
	B. Soils demonstration	1) Demonstration of iron mineralogy (already completed in Stage 3) sufficient to maintain insoluble uranium mineral stability	Same as Task 2A	Same as Task 2A
		2) Final geochemical modeling using site-specific data (iron mineralogy and uranium concentrations in groundwater/soils)	Same as Task 1A	Same as Task 1A

Appendix D

Soil Analytical Methods

Appendix D

Soil Analytical Methods

A variety of methods will be used to provide a comprehensive characterization of the soil in the aquifer in order to verify that iron minerals are transformed to iron sulfide. A description of these methods, with reference to their application for similar purposes, is provided as follows:

Selective chemical extraction: This method involves the use of chemical extractants that target specific mineral phases in the soil (Tessier, 1979). Various iron mineral phases are quantified according to their crystallinity, for example amorphous (poorly crystalline iron) is extracted using a solution of hydroxylamine hydrochloride in dilute hydrochloric acid and crystalline iron is extracted with a solution of citrate-bicarbonate-dithionite (Chao and Zhou, 1983; Poulton and Canfield, 2005). Poorly crystalline iron is the most accessible form of iron for microbial transformation, however with time the crystalline iron fraction will be altered. The shift in iron speciation during the course of remediation will be quantified using this technique (Figure D-1). Ferrous iron that is released due to reductive dissolution of iron oxyhydroxides in the aquifer, and subsequently re-adsorbed, will be determined by extraction with dilute (0.25N) hydrochloric acid (Gleyzes et al., 2002). Acid-volatile sulfide, combined with analysis of simultaneously-extractable metals (AVS-SEM), will be used to quantify sulfide, iron and the production of iron sulfide in the soil during remediation (Cooper and Morse, 1999). Finally, total metal content of the soil will be determined by EPA Method 3050 (acid digestion) and inductively-coupled plasma mass spectrometry (ICP-MS, EPA Method 6010) in order to understand the fraction of total iron that is available for biotransformation.

X-Ray Diffraction: This method will provide information about the bulk mineralogy at baseline and during treatment. Soil (~1 gram) is loaded into a sample holder for analysis using a powder x-ray diffractometer; mineral phases are identified based upon their x-ray diffraction (XRD) pattern. Patterns are matched against standards available in a powder diffraction database provided by the International Centre for Diffraction Data (ICDD). Iron mineral phases, if present at concentration greater than 1 percent by weight can be detected and the method can provide semi-quantitative information about these minerals and their transformation over time. Bulk minerals, such as quartz, feldspar, plagioclase, amphibole, and clay, will likely comprise most of the aquifer soil at baseline; the method will be used to screen the samples for the iron minerals. This method will also be used to detect iron sulfides, if present in sufficient quantity (>1% by weight) (Wilkin and Barnes, 1996). Synchrotron-based XRD will be used to examine mineralogy of the samples at a higher resolution and will provide information about microscopic crystalline phases that may not be detected by bulk XRD. The advantage of synchrotron-based XRD is the ability to maintain the sample in a sample holder sealed from contact with air thereby preserving the air-sensitive minerals. This method is available at high-energy x-ray sources, including the National Synchrotron Light Source at Brookhaven National Laboratory (New York), and the Advanced Photon Source at Argonne National Laboratory (Illinois). These resources can be accessed through appropriate arrangements with these Federal "user-facilities." The x-ray microprobe XRD method can also be used to obtain x-ray fluorescence (XRF) information (to identify elements in a sample and the co-association of elements (such as iron and uranium) has been applied to examine mineralogy at the scale of 10-microns in a sample, and for understanding the biotransformation of radionuclides in the environment (Lanzirotti and Sutton, 2006; Fuhrmann and Lanzirotti, 2005). Sulfide phases, and mineral phases present below the detection of bulk-XRD methods, have been identified in environmental samples using this method (Walker et al., 2005).

Microprobe Methods: In addition to synchrotron-based micro-XRD, other microprobe methods will be used to characterize the soil during the performance monitoring phase including scanning-electron microscopy (SEM) with energy-dispersive x-ray spectroscopy (EDS) (Figure D-2). This method provides even finer resolution (sub-micron resolution, down to nanometer scale). Samples will be analyzed using an environmental-SEM (ESEM); this instrument provides the capability to analyze the soil without the need for ultra-high vacuum (UHV). The UHV instruments require soil to be coated with a fixative (e.g., gold) or embedded so that the samples can withstand the UHV environment. The ESEM analysis will provide images (allowing identification of iron mineral based upon morphology) as well as elemental information from the EDS (providing for the detection of co-located iron-uranium-sulfur). Mackinawite has been characterized by SEM, as well as other forms of iron sulfide (Rickard, et al., 2006). Microprobe XRF and micro-x-ray absorption near-edge spectroscopy (μ-XANES) (synchrotron-based methods) will also be used to examine iron-uranium-sulfur associations and co-location within the soil (Reeder, et al., 2001) (Figure D-3).

References:

Chao, T.T., and L. Zhou. 1983. Extraction techniques for selective dissolution of amorphous iron oxides from soils and sediments. Soil Science Society of America Journal. 47: 225-232.

Fuhrmann, M., and A. Lanzirotti. 2005. ^{241}Am, ^{137}Cs, Sr and Pb uptake by tobacco as influenced by application of Fe chelators to soil. Journal of Environmental Radioactivity. 32: 33-50.

Gleyzes, C., S. Tellier, and M. Astruc. 2002. Fractionation studies of trace elements in contaminated soils and sediments: a review of sequential extraction procedures. Trends in Analytical Chemistry 21(6,7): 451-467.

Lanzirotti, A., and S. Sutton. 2006. Synchrotron X-ray microbeam techniques in assessing metal bioavailability in the environment. Geochimica et Cosmochimica Acta, 70: 343-346.

Poutlon, S.W., and D.E. Canfield. 2005. Development of a sequential extraction procedure for iron: implications for iron partitioning in continentally derived particles. Chemical Geololgy 214: 209-221.

Reeder, R.J., M. Nugent, C.D. Tait, D.E. Morris, S.M. Heald, K.M. Beck, W.P. Hess, and A. Lanzirotti. 2001. Coprecipitation of uranium(VI) with calcite: XAFS, micro-XAS, and luminescence characterization. Geochimica et Cosmochimica Acta 65(20): 3491-3503.

Rickard, D.T. 1975. Kinetics and mechanism of pyrite formation at low temperatures. American Journal of Science. 275: 636-652.

Tessier, A., P.G.C. Campbell, M. Bisson. 1979. Sequential extraction procedure for the speciation of particulate trace metals. Analytical Chemistry, 51: 844-851.

Walker, S.R., H.E. Jamieson, A. Lanzirottie, C.F. Andrade, and G.E.M. Hall. 2005. The speciation of arsenic in iron oxides in mine wastes from the Giant Gold Mine, N.W.T.: Application of synchrotron micro-XRD and micro-XANES at the grain scale. The Canadian Mineralogist, 43(4): 1205-1224.

Wilkin, R.T., and H.L. Barnes. 1996. Pyrite formation by reactions of iron monosulfides with dissolved inorganic and organic sulfur species. Geochimica et Cosmochimica Acta 60(21): 4167-4179.

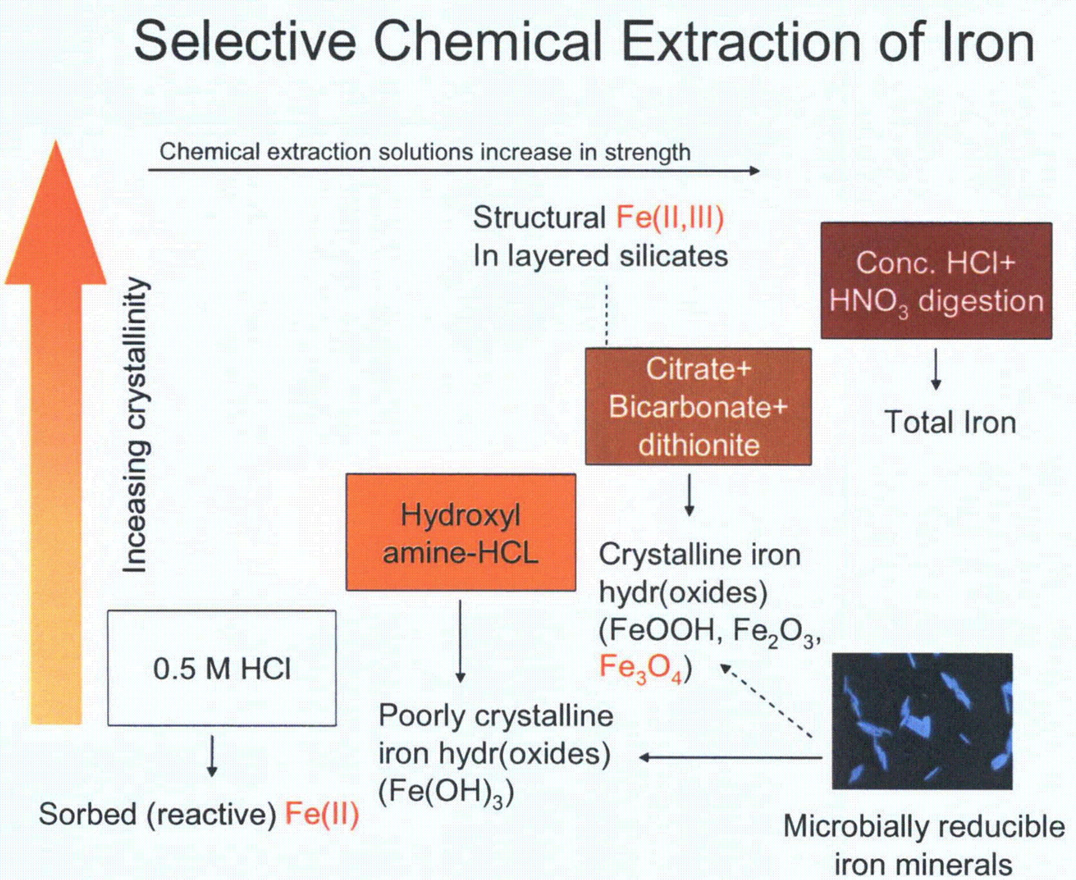
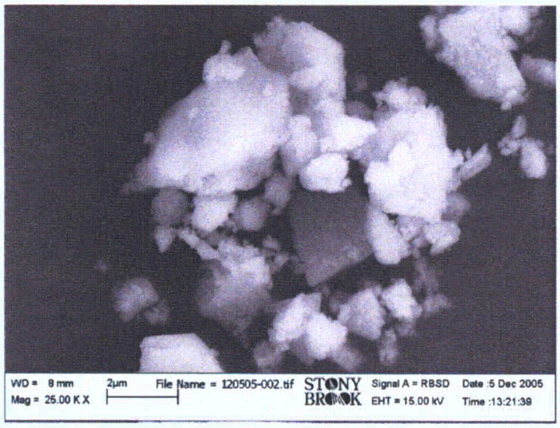
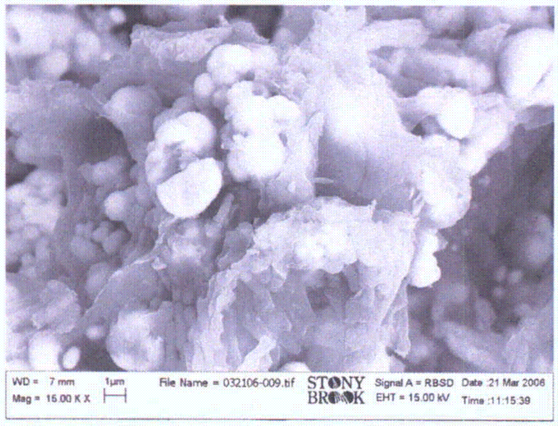


Figure D-1. Selective Extraction Scheme for Determining the Microbially Accessible Iron in the Aquifer During the Performance Monitoring Phase.





Prior to Microbial Activity: SEM of ferrihydrite ("2-line ferrihydrite" $Fe_5HO_8 \cdot 4H_2O$; surface area: 331± 2 m^2/g; 592 ± 1 ug Fe/mg)

After Microbial Activity: SEM analysis shows magnetite spherules (Fe_3O_4 (mixed-valent iron)), bacterial cells and exopolymer. Bacteria were grown on glucose.

Figure D-2. Scanning Electron Microscopy of Ferrihydrite (A) and Biogenic Magnetite Formed After Metabolism of Glucose (B) (from Gillow, in preparation).

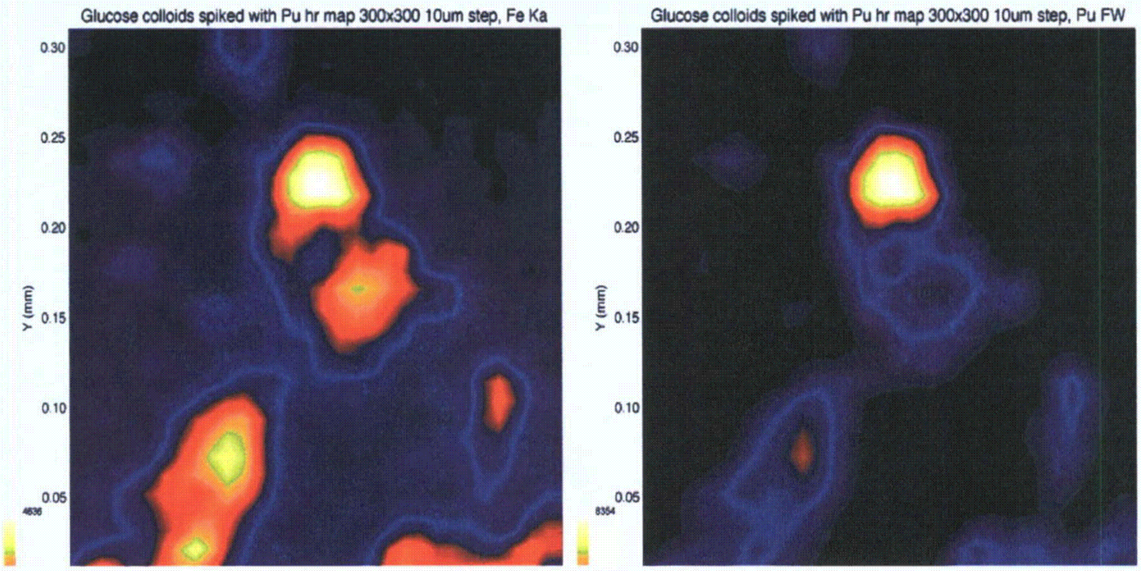


Figure D-3. Synchrotron Micro-x-ray Fluorescence of Iron Particles Spiked with Plutonium. Left panel (A) shows the iron distribution (false color image, yellow represents the highest concentration of Fe). The right panel (B) shows the Pu distribution. This method can identify spatial distribution of elements on a microscale in a sample (these images are 300 micron x 300 micron); each spot can be studied by μ-XANES to understand oxidation state and chemical speciation. (from Gillow, in preparation).

Appendix E

Quality Assurance Program Attachments

Appendix E
Quality Assurance Program Attachments

Cimarron Quality System Manual
Table of Contents

Section | Page

Appendix E
Quality Assurance Program Attachments

Appendix E
Quality Assurance Program Attachments

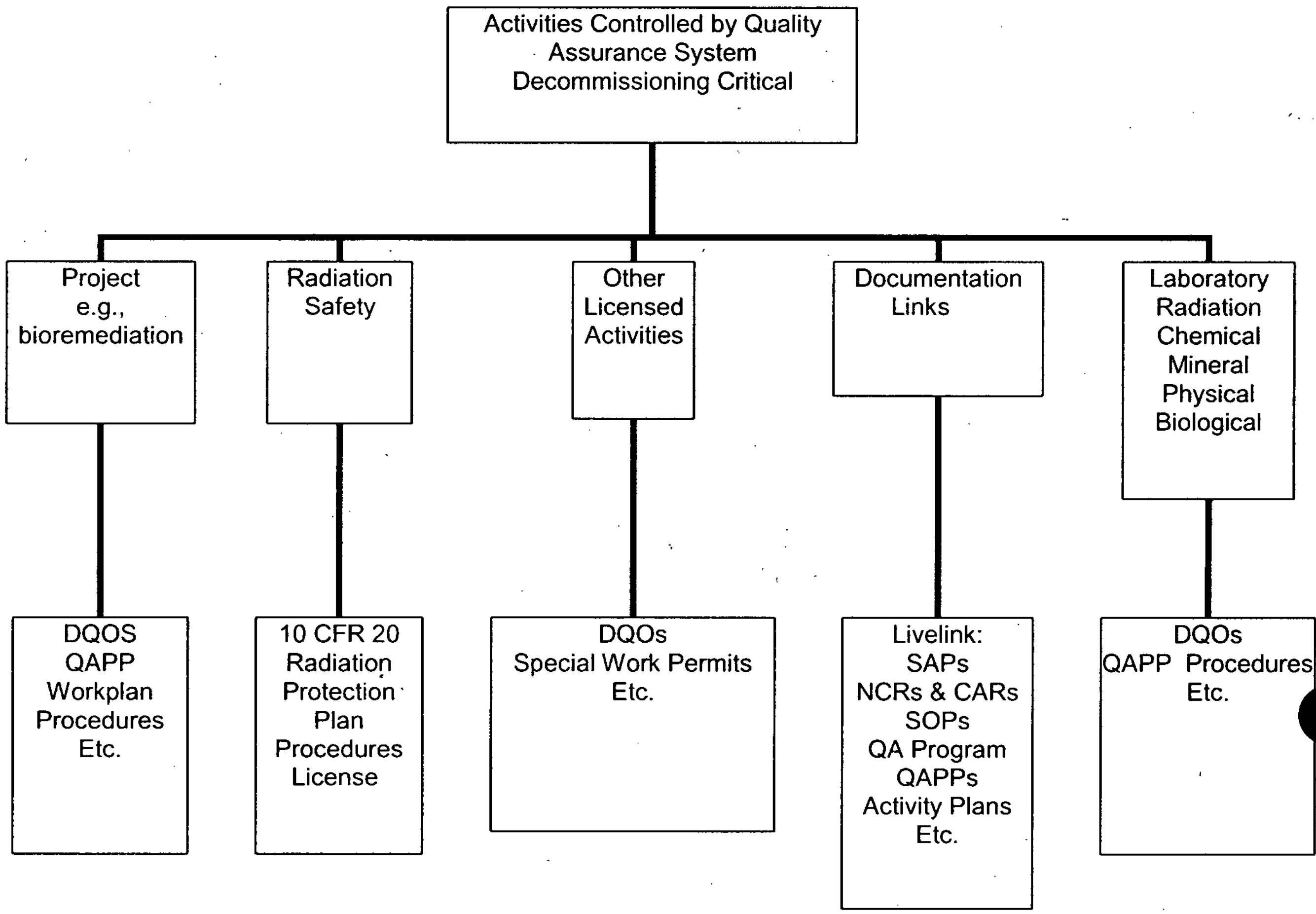
Appendix E
Quality Assurance Program Attachments

Table E-1
QA Cross References

Item Description	NQA-1 1994	RegGuide 4.15 Rev. 2	NUREG 1757, vol. 1	Cim QA System	ANSI/ASQ E4-2004
Organizational Structure and Responsibilities of Managerial and Operational Personnel	BR 1	C.1	17.6.1	1.0	5.2
Quality Assurance Program	BR 2	C, C.2	17.6.2	2.0	5.3,5.4
Design Control	BR 3	C.8	N/A	3.0	5.8,6.2, 6.3,7.2,7.3
Procurement Document Control	BR 4	N/A	N/A	4.0	5.5
Instructions, Procedures, and Drawings	BR 5	C.3	N/A	5.0	5.9,6.4.2
Document Control	BR 6	C.3	17.6.3	6.0	5.6
Control of Purchased Items and Services	BR 7	N/A	N/A	7.0	5.5
Identification and Control of Items	BR 8	N/A	N/A	8.0	
Control of Processes	BR 9	C.3	N/A	9.0	5.9
Inspection	BR 10	C.3	N/A	10.0	5.10
Test Control	BR 11	C.8	N/A	11.0	5.7,6.6,7.7
Control of Measuring and Test Equipment (MT&E)	BR 12	C.6.1	17.6.4	12.0	6.4.3,7.4.4, 7.5.5
Handling, Storing and Shipping	BR 13	C.3	N/A	13.0	6.4.4
Inspection, Test and Operating Status	BR 14	C.3	N/A	14.0	6.4.3
Control on Nonconforming Items	BR 15	C.10	N/A	15.0	
Corrective Action	BR 16	C.10	17.6.5	16.0	
Quality Assurance Records	BR 17	C.4	17.6.6	17.0	5.6
Audits	BR 18	C.9	17.6.7	18.0	5.10
Quality Control in Environmental Sampling	N/A	C.5	N/A	19.0	
Quality Control in the Radioanalytical Laboratory	N/A	C.6	N/A	20.0	
Internal Quality Control Samples and Analysis	N/A	C.6.2	N/A	21.0	
Performance Evaluation Program	N/A	C.6.3	N/A	22.0	
QAPP (Quality Assurance Project Plan)	N/A	B, para. 3	N/A	23.0	6.3.2 7.2.2

Appendix E
Quality Assurance Program Attachments

Chart E-1
Quality Assurance System



Appendix F

Modeling Output Files

Appendix G

Column Testing Procedure

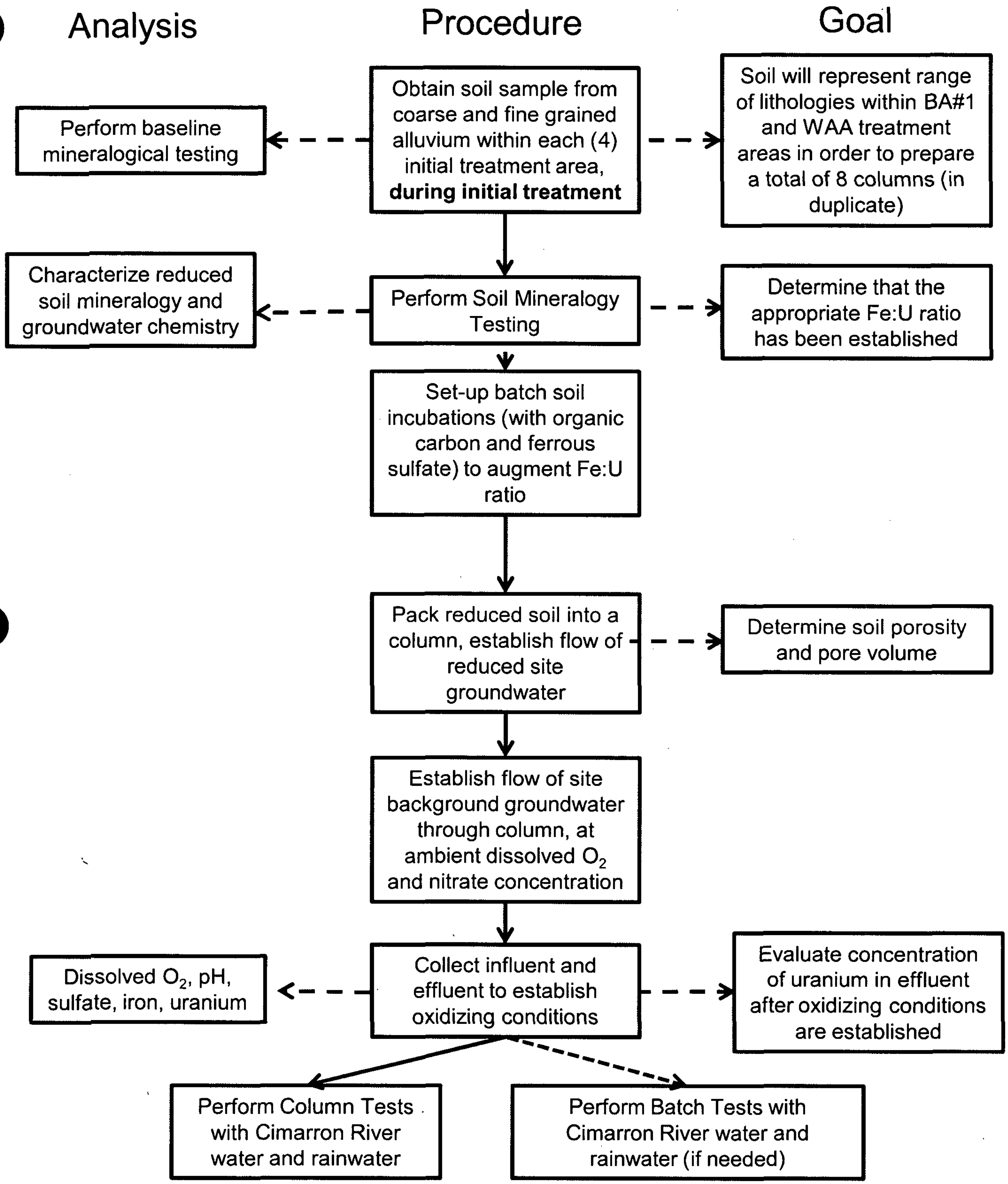


Figure 1. Column testing approach.

Attachment 1: Column Testing to Demonstrate the Protective Role of Iron Sulfide Relative to Uranium Immobilization

Jeff Gillow, Ph.D. and Boyce Clark, Ph.D.
ARCADIS, U.S., Inc.

March 6, 2009

1.0 INTRODUCTION

The NRC has requested a bench-scale test to examine the potential remobilization of uranium from soil after in situ treatment. This test will provide data to satisfy one of the four NRC acceptance criteria during the initial treatment testing phase prior to proceeding to full-scale in situ groundwater treatment. . This attachment presents a conceptual summary of the column test procedure as illustrated in the attached Figure 1; a detailed procedure will be prepared for the column study prior to the start of this work as required by the QA plan for the project.

The goal of the laboratory column testing will be to show oxygen consumption by the reduced minerals in the soil column and to demonstrate the conversion of iron sulfide to iron (hydr)oxide mineral phases. This analysis supports the remedy completion demonstration based upon the following:

- Demonstration that upgradient oxidants will be consumed by the aquifer soil validates the geochemical modeling and mechanisms upon which uranium immobilization, and maintenance of the immobilization is based.

- Demonstration that upgradient oxidants catalyze the conversion of iron sulfide to iron (hydr)oxides validates the mechanism of immobilization of uranium through sorption described by the geochemical modeling.

Similar testing was recently described by Thornton et al. (2007) to determine the lifetime of an iron-sulfide based barrier deposited in the vadose zone by hydrogen sulfide. Although the deposition method (hydrogen sulfide gas) proposed in this publication is much less robust than the creation of iron sulfide through microbial reductive dissolution of aquifer iron, subsequent iron sulfide precipitation, and introduction of additional iron proposed herein, the method of laboratory testing is relevant to this work.

2.0 CONCEPTUAL SUMMARY OF COLUMN TESTS

Soil samples will be collected from within the area of influence of the initial treatment system (as determined by tracer testing and performance monitoring). The soil samples will be collected after the initial treatment system has been operated for an appropriate amount of time (based upon the performance indicator data) to ensure coverage of the treatment reagents throughout the initial treatment area and within year 1.

ARCADIS will collect soil from borings located in four of the six initial treatment areas. The column tests can only be practically performed on samples of unconsolidated soils, so sandstone from Burial Area #1 and the Western Upland area will not be collected for column testing. This is reasonable because the fine-grained soil in the two transition zones and the cleaner sands of the deeper alluvium represent "ends of the spectrum", with the silty sandstone being in the middle of the spectrum. It is reasonable to presume that if the fine-grained soil and clean sands yield acceptable results in column tests, the silty sandstone would also yield acceptable results. Figure 5-2 defines the initial treatment areas. The soil samples that will be collected for column tests will come from the following four areas:

1) The downgradient portion of the area of impact in the sandy alluvium in Burial Area #1 (BA#1);
2) The transitional alluvium in BA#1 in the middle of the uranium area of impact;
3) The downgradient portion of the area of impact in the sandy alluvium in the Western Alluvial Area (WAA); and
4) The transitional alluvium in WAA in the middle of the uranium area of impact near the bedrock escarpment.

Therefore soil will be collected from locations dominated by sandy lithology (1 and 3, above) and dominated by finer-grained lithologies (2 and 4, above).

Groundwater samples corresponding to the groundwater in each of these four soil samples will be collected from impacted and unimpacted wells yielding water quality similar to that of the corresponding soil sample (based on information presented in Conceptual Site Model, Rev. 01). ARCADIS will ensure that site groundwater used in tests reflects the chemistry of groundwater associated with the soil sample used in the column test.

The soil samples collected from the initial treatment areas are anticipated to have increased iron sulfide from the initial treatment activities, but will not have the required 80:1 ratio of iron to uranium in this reduced treatment time frame. As a result, reducing conditions will be created in the laboratory in each batch of soil samples and corresponding groundwater from an impacted well until the required ratio of iron sulfide to uranium is achieved. Once this ratio is achieved, the soil will be packed into columns for the column tests. The reducing phase will involve a batch incubation and the oxidizing phase will be a column test. For the reducing phase, the soil will be placed into glass bottles and site groundwater containing uranium will be added to the bottle along with amendment (organic carbon) and reagents (ferrous sulfate). The bottle will be purged with nitrogen to remove air from the headspace, and reducing conditions will be established (through the introduction of organic carbon to stimulate microbial activity [identical to the process used in the field]) to promote the precipitation of uranium in the soil and to create additional iron sulfide. The batch incubation method for the reducing phase of the test will provide the opportunity to remove samples of groundwater and soil. Analysis of samples that are periodically removed from the bottles will provide a means to track the progress of uranium reduction as well as the production of iron sulfide.

After the mass of iron sulfide is created and uranium is precipitated to achieve the 80:1 Fe:U mass ratio, the reduced soil will be packed into a column. Site groundwater (collected from an area outside of the uranium impact) will then be introduced into the column. This groundwater will have dissolved oxygen at an ambient site concentration (approximately 3 mg/L) as well as background concentrations of nitrate, and represents future groundwater entering the areas of impact from upgradient. Dissolved oxygen and sulfate will be monitored in the column effluent, and the uranium concentration will be measured during the establishment of oxidizing conditions in the groundwater.

In addition, the column tests will be conducted using Cimarron River water with water quality representative of river water at flood stage and rainwater to simulate oxidizing conditions produced by infiltration of either river water or rainwater. River water will be used because it potentially has a higher concentration of nitrate than groundwater; this will be verified through analysis. Both during leaching and after oxidizing conditions are established, samples of the effluent from each column will be analyzed for uranium to demonstrate that the iron sulfide has retarded the remobilization of uranium at concentrations exceeding the release criteria.

Soil mineralogical analyses will be performed of the soil samples collected for column testing prior to starting the column test, and at the end of the establishment of oxidizing conditions in the column. These analyses will also be performed in the field during operation of the initial treatment system as described above. The results of the mineralogical analyses of the soil used in the column tests will serve as a benchmark data set for comparison with the field results. In this manner, fingerprints in the soil mineralogy, indicative of longevity for uranium immobilization, will be established and then sought and tracked in the mineralogical analyses of soil samples collected from the field.

3.0 COLUMN TESTING PROCEDURE

3.1 Soil Sampling

Soil samples will be retrieved from BA#1 and from the WAA within the alluvial initial treatment areas. . The soil samples will be taken with an acetate-lined steel core sampling sleeve of the appropriate diameter (~1.5 inches) and length (~3-4 feet, or multiple 1-foot cores). Upon removal from the subsurface, the core(s) will be capped with plastic and wrapped with parafilm and vinyl tape and placed in a cooler on dry-ice. A glove box filled with inert gas (nitrogen) will be available at the sampling location in order to prepare the core for shipment; EPA guidance (Wilkin, 2006) will be followed for anoxic soil sampling. The sample will be shipped to a University laboratory (Colorado School of Mines or equivalent lab that maintains a license to handle radioactive material [enriched uranium]).

3.2 Soil Mineralogical Testing

Prior to commencing column testing, the core sample will be analyzed for baseline mineralogy. The core will be extruded, homogenized by mixing, and subsamples will be removed (at 4 locations along a 1-ft core) for analysis of the following:

1) Total uranium and iron content by acid digestion and ICP-MS.
2) Extractable iron by dilute hydrochloric acid extraction (for amorphous iron)
3) Extractable iron by citrate-bicarbonate-dithionite extraction (for total iron oxyhydroxide).
4) Acid-volatile sulfide and simultaneously extractable metal analysis (AVS-SEM) to determine the iron sulfide content.
5) Acid-base accounting analysis (ABA) to determine the amount of sulfide-sulfur present in the soil.
6) Based upon the results of 1-5, above, select samples (1 to 2 from each core) will be analyzed by Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy and X-ray Absorption Spectroscopy (μ-X-ray fluorescence [μ-XRF]) and μ-X-ray absorption near edge structure analysis (μ-XANES).

The results of this analysis will constitute baseline soil mineralogical testing.

3.3 Column Testing with Site Background Groundwater

The baseline geochemical modeling specifies that the concentration of reactive iron required for protection of the immobilized uranium, relative to re-oxidation over 1000 years, is 0.03 wt % (300 mg Fe/kg soil). In addition, the 80:1 Fe:U mass ratio is also specified by the baseline geochemical modeling to provide enough total sorptive capacity to immobilize any uranium that may be oxidized. Treatment is complete when these two criteria are met. If the soil recovered from the initial treatment area meets the criteria established by the baseline geochemical modeling then it will be used directly in the column testing. However, if the criteria are not met, then the soil samples will be treated further in the laboratory to achieve the specified minimum 80:1 Fe:U mass ratio. In this case, batch incubations will be performed and the soil samples will be treated with organic carbon and ferrous sulfate to establish these conditions in the laboratory. Multiple batches will be prepared so that adequate material is available for the column test, and the batches will be analyzed for the appropriate mineralogy. Details of the treatment procedure are provided here.

After baseline soil mineralogy sampling, the soil will be placed into thick-walled, wide-mouthed screw-top glass bottles with Teflon-lined plastic closures. This will be done inside of an anaerobic (nitrogen-filled) glove box. Site groundwater will be added (after purging with nitrogen gas) and molasses and ferrous sulfate will also be added to stimulate additional microbial activity and provide a substrate for the formation of iron sulfide. Reducing conditions will be established and confirmed through the analysis of dissolved uranium, iron, and sulfate. A subsample of soil will be removed and analyzed for iron sulfide and uranium in the solid phase. Once appropriate conditions are met (specified above), the liquid will be decanted and the soil will be removed with a stainless-steel spatula and wet-packed (using the liquid decant from the batch incubation) into the column. Once filled with soil, the 2-foot, approximately 4-inch diameter thick-walled clear PVC column will be capped at either end and mounted vertically inside of an anaerobic glove box (note that smaller columns may be used based upon refinement of this procedure once the samples have been recovered from the field). Columns will be prepared in duplicate to provide a replicate data set for each treatment area. The end-caps will consist of in-line 1 micron filters to prevent soil particles from exiting the columns. The weight of the soil added to the column will be recorded. Column testing will proceed as follows:

1) Anoxic site groundwater (prepared by purging site groundwater with nitrogen to remove dissolved oxygen) will be allowed to flow through the column, in an upflow direction, until it is fully saturated. The flow of anoxic site groundwater through the column will continue for 1-2 days at which point the pH, dissolved oxygen, iron, uranium, and sulfate concentration in the water will be measured. This will establish baseline effluent parameters.

2) Site background groundwater at ambient oxygen concentration, along with a conservative tracer (fluorescein or rhodamine) will be introduced into the column. The dissolved oxygen content of the influent water will be measured, as well as pH, sulfate, and nitrate concentrations in the influent water. The conservative tracer will be used to determine column pore volume and to examine the retardation of dissolved oxygen through the column.

3) Samples will be collected at each pore volume (flow will be established so that replacement of one pore volume requires approximately 1-2 days) and measured for tracer concentration, pH, dissolved oxygen (using an in-line dissolved oxygen probe), dissolved iron, dissolved uranium, and sulfate and nitrate.

4) The column experiment will be terminated when any one of the following criteria are met:

   - 5 days after dissolved oxygen breaks through the column
   - Uranium breaks through the column at >180 pCi/L

We will frequently monitor for dissolved oxygen breakthrough, and once observed, we will collect samples to determine the trend in uranium concentrations. If for example at approximately 60 days of operation at a flowrate of 1 pore volume every 2 days, we observe dissolved oxygen breakthrough, then we will have simulated ~125 years of groundwater flow. This duration of simulated flow is based upon the 1-D geochemical modeling (Section 3.4.3.3 of the GDP) in which one pore volume represents 4.2 years of flushing with groundwater. Based upon the data obtained up to and 5 days past the point where oxygen breaks through, we will extrapolate to performance over 1,000 years. This extrapolation will be based upon the results of the concentration of uranium in the column effluent, the rate of uranium leaching (if any), and the remaining mass of uranium in the column (determined by mass balance calculation).

3.4 Column Testing with Additional Water Types

A reoxidation column test will be performed using BA#1 soils and Cimarron river water. The river water will be substituted for site background groundwater in the testing procedure. The river water will be analyzed prior to use to determine the concentration of dissolved oxygen, nitrate, and other constituents. If possible, Cimarron river water will be collected at flood stage and used in the reoxidation column test. In addition, a reoxidation column test will be performed using WAA soils and rain water. The rain water will be collected during the time of the year with the highest average precipitation; the collected water will be analyzed for baseline chemistry prior to use.

Additional testing of BA#1 soil with rain water and WAA soil with river water may be performed in batch tests if the results of the column tests yield different results than the tests with baseline site groundwater. Batch testing will provide a means to limit the need to perform an excessive number of column tests. Batch tests will involve the addition of the oxic water to the reduced soils in a serum bottle and measurement of loss of dissolved oxygen, nitrate, and other oxidants from the water and corresponding measurement of dissolved sulfate and uranium. The batch tests will be simpler to perform than column tests and will provide information about the potential reoxidation of uranium with the other sources of oxic water, however, extrapolation over the 1,000 year period will be more difficult as compared to the advective groundwater flow column experiments.

4.0 SUMMARY

The column test described above has been developed in specific response to an NRC request. It is one of four acceptance criteria specified by the NRC to be met by the initial treatment area testing prior to advancing to full-scale treatment. The column test is intended to demonstrate that the iron sulfide geochemistry necessary to sequester uranium in soils can be established, thereby preventing uranium concentrations in groundwater from ever exceeding a threshold value of 180 pCi/L. Specifically, results obtained from the column test will be used to demonstrate that 1) uranium in groundwater in Burial Area #1 and the Western Alluvial Area can be reduced to and maintained at concentrations below the 180 pCi/L treatment level after ambient (oxygenated) conditions return (following completion of active remediation) and 2) that post-treatment, uranium concentrations in groundwater will permanently remain below the 180 pCi/L treatment level. The results of the column test will also be used to meet condition (D) (Figure 5-1) for license termination. In addition to providing the requested demonstration, information obtained from the column study will be used to optimize the amendment applications performed in the field during full-scale implementation to create the widespread geochemical conditions required to achieve lasting treatment of the groundwater impacted by uranium.

5.0 REFERENCES

Thornton, E.C., L. Zhong, M. Oostrom, and B. Deng. 2007. Experimental and theoretical assessment of the lifetime of a gaseous-reduced vadose zone permeable reactive barrier. Vadose Zone Journal 6: 1050-1056.

Wilkin, R. 2006. Mineralogical Preservation of Solid Samples Collected from Anoxic Subsurface Environments. EPA Ground Water Issue, EPA/600/R-06/112, October 2006.

Appendix H

Groundwater Decommissioning Cost Estimate Detail